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A Study of the Rearrangement of the Crystals of a Metal by Its Recrystallization

By Usaburo Yoshida and Saburo Nagata

(Received Sept. 18, 1936)

Abstract

By means of an X-ray examination of thin plates of aluminium, it was observed that the germination process, in the case of sudden heating to the germinative temperature range, took place in two stages with a cold worked aluminium plate: primary grain growth to a moderate size starting from a very minute one, and then the secondary grain growth to exaggerated size starting from the moderate one. As to the orientation of the crystal formed by recrystallizing elongated thin aluminium plate consisting of its single crystal with gradual heating, it was found that when the elongation was less than about 2 percent the new crystal formed by recrystallization retained one of the orientation before recrystallization which had been occupied by one of the micro-crystals formed by crushing the single crystal by the process of stretching; and that when the elongation was greater than about 2 or 3 percent the orientation of the new crystal formed by recrystallization was independent from those of the micro-crystals before recrystallization.

In a paper[1] recently published the writers stated that the grain growth of metal crystals to a considerable size by recrystallization in the germinative temperature range did not take place directly by consuming the initial minute crystallites which had suffered some distortion by a previous cold working, but that it was produced by repeating several times (two times probably) the process of melting and crystallization, as was manifested by rather even or uniform grain growth of the metal crystallites at a rather lower recrystallization temperature. This point being very important in understanding the process of recrystallization of metals, the present experiment to elucidate it was carried out with thin commercial aluminium plate. The size of all the test pieces was 10 cm × 1.5 cm × 1 mm. These test pieces were first annealed for 48 hours at the temperature of 320°C, and then were stretched in various degrees of elongation ranging from 1 to 5 percent. Each test piece was then put suddenly, and for various durations of time, into a furnace always kept at the temperature of 630°C. This temperature is certainly within the germinative temperature range for

1. U. Yoshida, S. Nagata and Ch. Mitsuki: These Memoirs, **19**, 169 (1936).

the test pieces stated above. As it was necessary in the present case to inspect with X-rays the manner of the grain growth in the intermediate stage of recrystallization, each test piece was subjected suddenly and successively to the same recrystallization temperature for various durations of recrystallizing time ranging from twenty or thirty seconds to several minutes by inserting into and taking out of the furnace alternately. An X-ray diffraction photograph was taken at every stage of manipulation.

Table I

State of the test piece	Manipulation of the test piece	State of the test piece	Manipulation of the test piece
a	commercial Al plate	*g*	*f* annealed at 630°C, 4 minutes
b	*a* annealed at 320°C, 24 hours	*h*	*g* annealed at 630°C, 2 minutes
c	*b* elongated 1.3%	*i*	*h* annealed at 630°C, 3 minutes
d	*c* annealed at 630°C, 20 seconds	*j*	*i* annealed at 630°C, 5 minutes
e	*d* annealed at 630°C, 1 minute	*k*	*j* annealed at 630°C, 5 minutes
f	*e* annealed at 630°C, 2 minutes		

An example of such manipulation of a test piece elongated by 1.3 percent is shown by Table I, and some of the X-ray photographs taken at the different stages of manipulation are reproduced in Fig. 1, Plate I. Any one of the photographs represented by *a*, *c*, *h* and *k* corresponds respectively to the stage of the test piece which is denoted by the same letter in Table I. Thus Fig. 1_a is obtained from the original commercial aluminium plate, Fig. 1_c from the test piece elongated 1.3 percent after the annealing at 320°C for 24 hours, Fig. 1_h from that subjected five times successively to the higher recrystallization temperature of 630°C, and Fig. 1_k from that subjected more three times successively to the same recrystallization temperature. In this last *k* state many minute Laue-spots, which were visible in earlier stages of recrystallization, were almost entirely displaced by a few stronger ones. This indicates that the germination is almost completed in this state, and any change in the distribution and the intensity of the Laue-spots was not detected on more prolonged subjection to the same recrystallization temperature. Fig. 1_h corresponds to an intermediate stage of the germination; and this photograph shows us, in addition to a few stronger Laue-spots which are the same as those seen in Fig. 1_k, the presence of a large number of minute and distinct Laue-spots whose appearance is clearly different from those in Fig. 1_c.

The diffused appearance of the Laue-spots, and consequently a rather continuous impression in Fig. 1_c, is of course due to the presence of an immense number of very tiny crystallites scattered rather evenly to some extent in their orientations. These very tiny crystallites grow up first into larger ones, as is observed by the presence of a large number of minute and distinct Laue-spots in Fig. 1_b; and then the crystallites thus grown develop to one or a few adult crystals in the process of germination, as is shown by the presence of a few strong Laue-spots in Fig. 1_k. From these facts it does not seem absurd to say that the growth of the crystals in the germination of a cold worked metal takes place roughly in two stages: first, from very tiny crystallites to those of intermediate size, and then to the adult size from the intermediate one. Here it must be noted that, in taking the Laue-photographs at various stages of manipulation of a test piece, special care was always taken to illuminate the same portion of the specimen with the pencil of X-rays. The photographs reproduced in Fig. 2, Plate I represent another example of the manner of crystal growth in the process of germination of a commercial aluminium plate, which is the same as in the case of Fig. 1. These photographs were taken by the long slit method so as to be capable of revealing a larger portion at once. Fig. 2_a was taken with a specimen obtained by annealing a commercial plate of aluminium at 320°C for 24 hours, by elongating it 3 percent and then by subjecting it to the recrystallization temperature of 620°C for 1.5 minute. With this short duration of recrystallizing time no indication of recrystallization could be detected. Fig. 2_b was obtained when the same test piece was heated suddenly for 2.5 minutes more at the same recrystallization temperature. It corresponds to an intermediate stage of germination. Fig. 2_c was obtained when the same test piece was heated still more suddenly for 5 minutes at the same recrystallization temperature. This corresponds to the stage of completed germination. These photographs seem to reveal the same aspect of the crystal growth in the germination process as in the case of Fig. 1, Plate I. Moreover, a close inspection of Fig. 2_b and Fig. 2_c shows us the manner of the crystal growth minutely in an interesting manner.

Next, the writers prepared many single crystal plates of aluminium by the ordinary stress-annealing method, and stretched them separately in various degrees of elongation ranging from 0.9 to 9 percent of the original length. These plates were then recrystallized at a temperature

of about 610°C for various durations of time ranging from several to about 20 hours, the temperature being raised gradually from the room temperature. The orientation of the aluminium crystals thus formed by recrystallization was examined by taking Laue-photographs of the specimens before and after the recrystallization respectively. A mere comparison of the two Laue-photographs taken before and after the recrystallization of the same portion of the specimen, will show clearly whether the orientation of the new crystal formed by recrystallization changed from or recovered that of the crystal before recrystallization. Three examples of such Laue-photographs are reproduced in Figs. 3, 4 and 5 in Plate II. In the case of Fig. 3, where the elongation was 2%, the photographs were taken by the long slit method. In this plate, Fig. 3_a corresponds to the original single crystal plate, Fig. 3_c to the recrystallized one and Fig. 3_b to the elongated one before recrystallization. The scattering of the orientations of the crystallites formed by crushing the original single crystal by the process of elongation is sufficiently perceptible in the diffuseness of the Laue-lines in Fig. 3_b. Such diffuse Laue-lines became perfectly sharp with recrystallization, as is seen in Fig. 3_c. Their position in this figure coincides perfectly with those in Fig. 3_a, showing that the orientation of the new crystal formed by recrystallization recovered that of the original crystal before recrystallization. The photographs reproduced in Figs. 4 and 5 in Plate II were taken by the ordinary Laue-method. Figs. 4_a and 5_a correspond to the elongated single crystal plates before recrystallization, and Figs. 4_b and 5_b correspond to the recrystallized plates respectively. In the case of Fig. 4 the photographs show that the orientation of the new crystal formed by recrystallization recovered that occupied by some one of the crystallites in the elongated test piece before recrystallization, as in the case of Fig. 3. Contrary to such examples the photographs in Fig. 5 show that the new crystal formed by recrystallization took a new orientation which was entirely different from those of the crystallites in the elongated plate before recrystallization. The writers carried out the same experiment with many single crystal plates of aluminium which were elongated differently, and the results obtained are tabulated in Table II. As is seen in the table, the orientation of the new crystal formed by recrystallization recovered, with only one exception, that of some one of the crystallites before recrystallization when the elongation was less than about 2%, while it changed always by recrystallization when the elongation

Table II

Elongation in %	Orientation of the recrystallized crystal	Elongation in %	Orientation of the recrystallized crystal
9.2	changed	2.7	changed
9.1	changed	2.6	recovered
7.4	2 crystals, both changed	2.5	2 crystals, one recovered, the other changed
6.1	changed	2.0	recovered
5.2	many crystals	1.6	recovered
5.2	changed	1.5	recovered
3.7	changed	1.5	recovered
3.6	2 crystals, both changed	1.4	recovered
3.2	2 crystals, both changed	1.3	recovered
3.1	recovered	1.1	2 crystals, one recovered, the other changed
2.9	changed	0.9	recovered

was greater than about 3.2%; and with elongation between these two limits, the results were mixed. Before this experiment a similar one with aluminium was performed by K. Tanaka[1] who elongated the single crystals within the range of 4-20 percent, and found that the new crystal formed by recrystallization took a new orientation which was rather independent from those of the crystallites before recrystallization. Thus his result agrees with the present when the elongation is greater than about 3 or 4 percent.

In a theory of the recrystallization of metals[2] proposed by one of the writers and Koyanagi, it was assumed that distorted metal crystals were easier to melt, and that the boundaries of metal crystals were more easily melted than their interior; and the independence of the orientation of the new crystals from those of the crystallites before recrystallization was considered to be due to the spontaneous formation of new crystal nuclei in the melt at the crystal boundaries. Though the results obtained in the present experiment as stated above seem to contradict to some extent this consideration, actually they do not. The results may be made clear by a detailed explanation of the theory. When the elongation of the single crystal plate is little, we can expect the persistence of a few undistorted small crystal fragments among an immense number of distorted fragments. If such is the case, it seems natural to suppose that some of the crystal fragments lying just in the immediate neighbourhood of such undistorted frag-

1. K. Tanaka: These Memoirs, **11**, 229 (1928); and **13**, 117 (1930).
2. U. Yoshida and K. Koyanagi: These Memoirs, **18**, 9, (1935).

ments are pretty severely distorted. If the temperature of such specimen is gradually raised to its recrystallization temperature, the severely distorted crystal fragments will melt and immediately adhere to the neighbouring undistorted fragments, resulting in the growth of the undistorted crystal fragment without the formation of any new crystal nucleus in the melt. Consequently the undistorted crystal fragment itself becomes the recrystallization nucleus in this case and the process of recrystallization proceeds from this nucleus. The recovery of crystal orientation by recrystallization with a little elongation is understood to take place in such a manner. When the elongation is much greater the persistence of such undistorted crystal fragments is not conceivable, and the recrystallization nucleus ought to be formed spontaneously in the melt at the crystal boundaries in the process of recrystallization; and thus the orientation of the new crystals becomes independent of those of the crystallites before recrystallization.

A similar experiment on the orientation of the crystals formed by recrystallizing elongated aluminium single crystal plates was also performed by suddenly subjecting the specimens to the recrystallization temperature of 610°C. But so far as the present experiment is concerned, the writers could not observe that the recrystallized crystals recovered the orientation of the old crystallites even with the elongations less than 2 percent. Moreover the number of the crystals formed by recrystallization was generally larger than in the case of gradual heating, as was expected by the former experiment[1] on the effect of sudden heating upon the grain size. In the case of sudden heating, the localities in the specimen, where the distorted crystallites melt and turn out to the recrystallization nuclei, become immense, as was stated in the former paper; and the recrystallization nuclei are formed spontaneously at the localities other than the immediate neighbourhood of undistorted crystal fragments. This seems to be the reason for the difficulty of the recrystallized crystals to recover orientation when the specimen is heated suddenly to its germination temperature. In the paper[2] cited a recrystallization experiment was described in which a cold worked aluminium plate was first subjected suddenly to a lower recrystallization temperature for some hours, after which the temperature was raised gradually up to a second higher recrystallization temperature belonging to the germinative temperature range. From

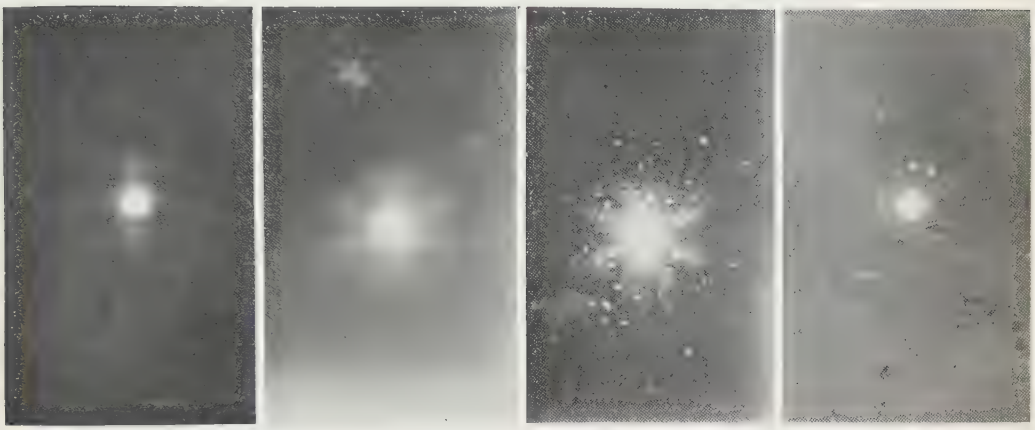
1. U. Yoshida, S. Nagata and Ch. Mitsuki: These Memoirs, **19**, 169, (1936).
2. ibid.

the number of the crystals thus formed per unit area on the surface of the specimen, it was considered that the healthy perfect crystal nuclei which had the ability to grow further and further in the germinative temperature range, or the localities where such nuclei were to be formed were already seeded in the first stage of lower recrystallization temperature; and that the germination was nothing but the growth of such healthy crystal nuclei. This rather ambiguous idea regarding the seeding of the crystal nuclei seems much clearer now in the present experiment on the recovery of the orientation of the recrystallized crystals, and it seems more reasonable to consider that the seeding is nothing but the formation of some undistorted crystal nuclei in the lower recrystallization temperature, which have the ability to grow further and further in the germinative temperature range.

In conclusion, the writers' sincere thanks are due to the Hattori Hoko Kai for their grant given to one of the writers (U. Y.), with the aid of which this research was accomplished.

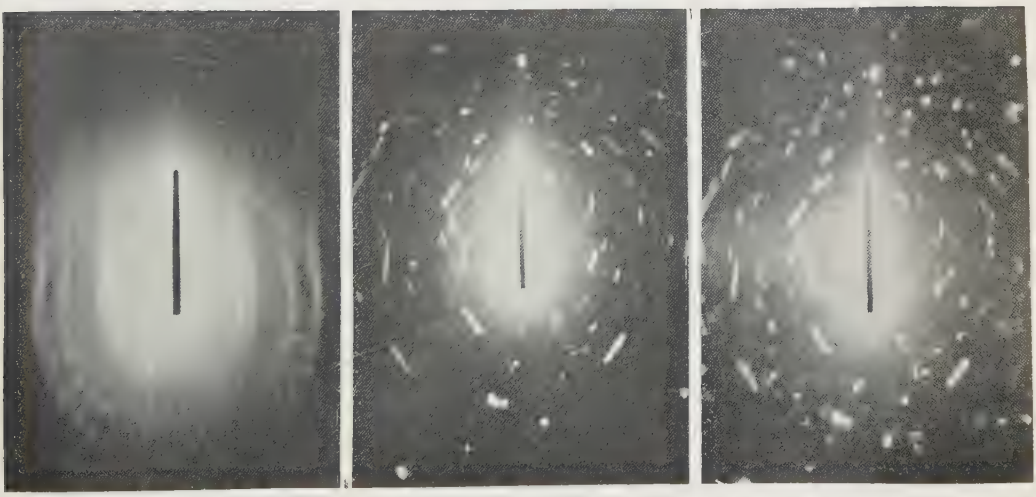
Plate I

Fig. 1



a *c* *h* *k*

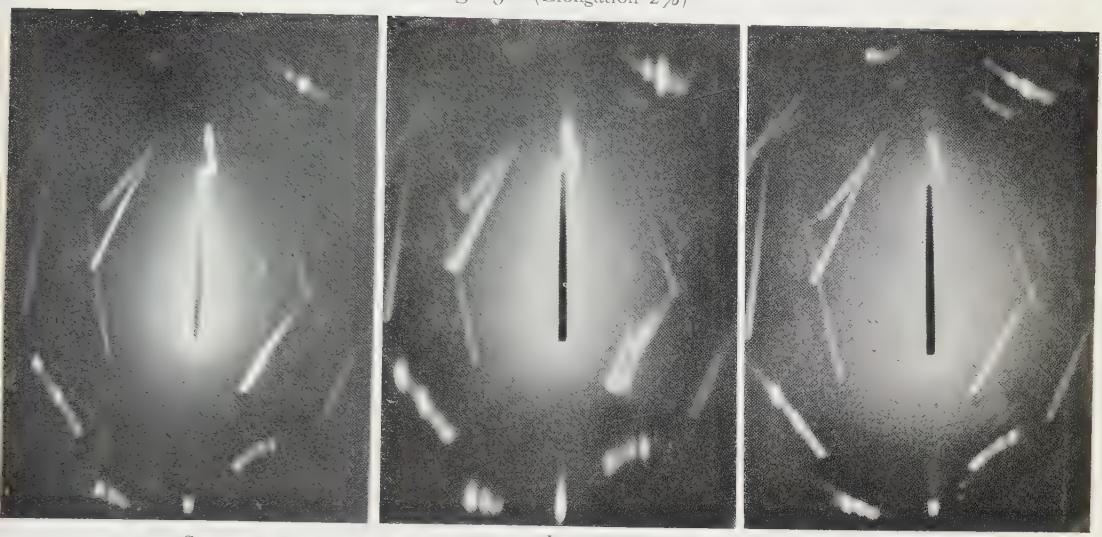
Fig. 2



a *b* *c*

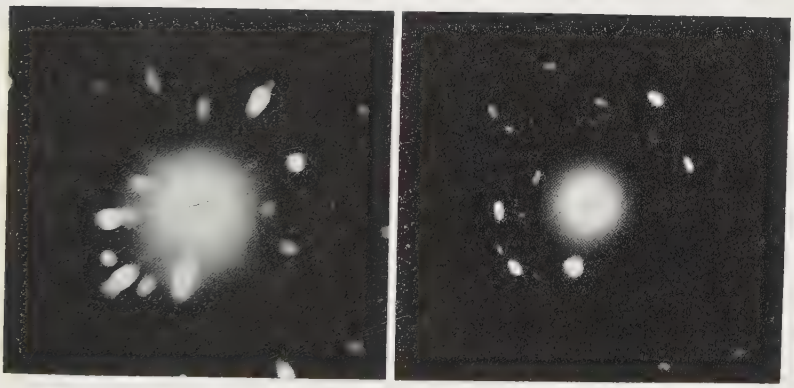
Plate II

Fig. 3 (Elongation 2%)



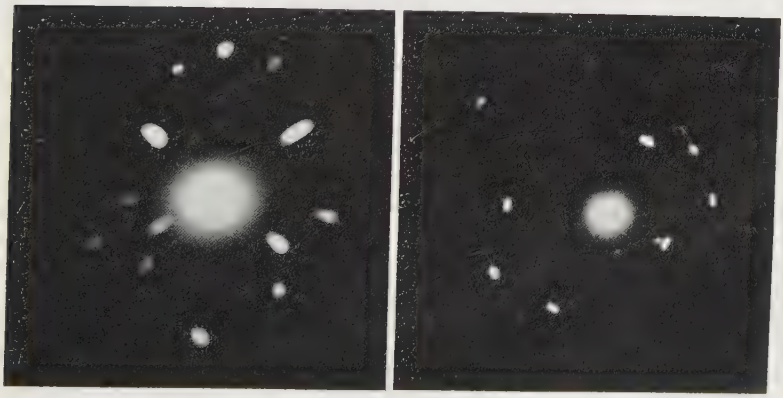
a *b* *c*

Fig. 4 (Elongation 2%)



a *b*

Fig. 5 (Elongation 2.7%)



a *b*

Changes in the Density of Silver with Annealing and Cold Working

By **Atuomi Igata**

(Received Sept. 18, 1936)

Abstract

With pure silver bar the changes of its density with the heat treatment and with the cold working were measured, and their relations were made clear in a systematic manner. The presence of minute cavities in the metal is discussed on the basis of the experiments. Finally, the process of obtaining the criterion value of the density of silver is proposed.

With respect to the density of metals and alloys several invetigations have been made in various ways. In the present experiment silver, more than 99.95% pure, was used as a specimen, and its density was measured after several annealings and cold rollings. The specimens which the writer examined were prepared by rolling (to about 50% reduction in thickness) cast silver bars, into long bars, the cross section of which was 4 mm × 10 mm. For annealing an electric resistance furnace was used, its temperature being measured by a thermo-junction. The porcelain pipe of the furnace which contained the specimens could be evacuated to a pressure lower than 0.1 mm Hg, or be filled with nitrogen or other gases of the same atmospheric pressure. The temperature of the furnace was raised to a given value in about 30 or 40 minutes, and was kept there for about 3 hours; then the specimens were left to cool in the furnace. A chemical balance was used for the density measurements. Before weighing in water, first the metal piece was sealed in a glass tube after the evacuation to a pressure lower than 0.1 mm. Hg., then the thin neck of the sealed glass tube and the glass tube itself were broken in the pure water previously boiled. This process was to get rid of the effect of the gas adhering to the surface of the test piece. In determining the density of the specimen necessary corrections due to the buoyancy of the air and the change of the densities of water and silver with temperature were always made. In the present experiment the values of the densities of all the specimens were recalculated to those at 17°C.

The changes of density of the specimens caused by successive annealings were seen to be represented by similar curves obtained by annealing in any furnace: air, nitrogen or vacuum, as seen in Figs. 1, 2, 3. In these curves we can see clearly that there is a maximum density at the annealing temperature of about 200°C–300°C, and a minimum density at about 600°C–800°C. In the following the writer will consider the significance of the parts, A, B, C, D in the above curves.

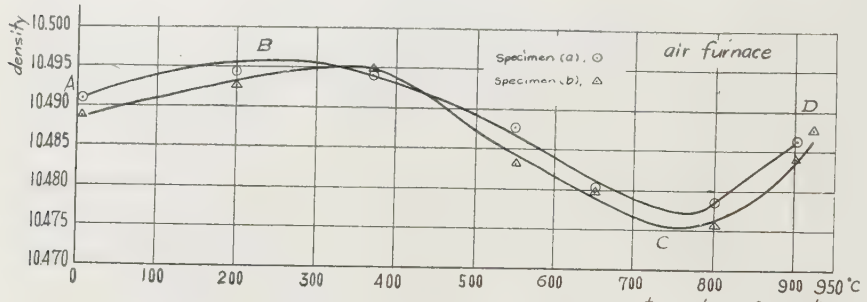


Fig. 1

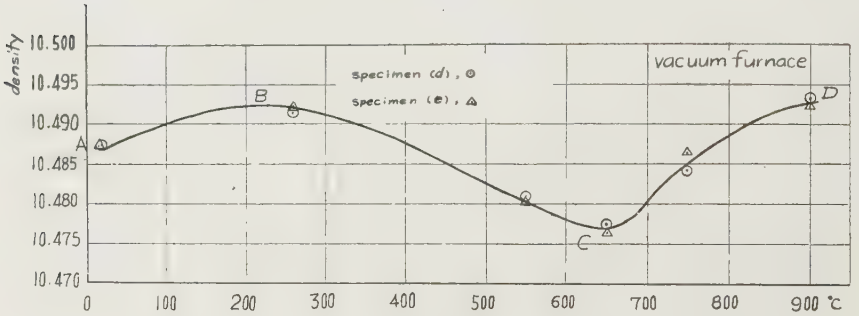


Fig. 2

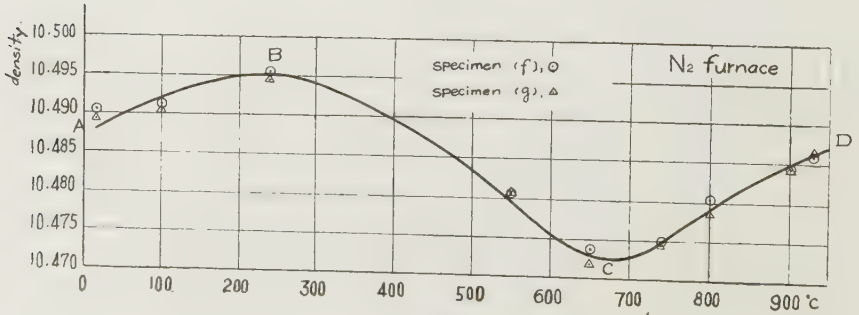


Fig. 3

It is natural that the density at the part A is different according to the previous history of the specimen such as casting, forging, cold working and heat treatment. The difference between the densities at the points A and B, as is seen in Figs. 1, 2, 3 and 10, is approximately of the order of $5/10^4$ of the density. This increase seems to be due to the recovery from the density decrease caused by the presence of the internal stress at the beginning. That this decrease is caused by the rolling to about 50%–70% reduction in thickness is shown in Fig. 4: that is, when the specimen in the B state is subjected to the rolling to 60%, its density decreases by $5/10^4$, and after the annealing at 210°C it increases again by the same amount.

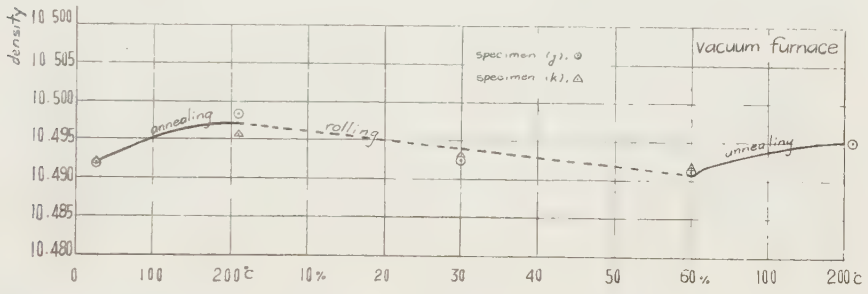


Fig. 4

When the degree of rolling increases more than a certain degree, the annealing temperature to recover the density becomes gradually higher. For the specimens rolled to about 80%–90%, the recovering temperature is about 600°C, as seen in Figs. 11, 12. For the less rolled specimen, the recovering temperature becomes lower as is seen in Fig. 10. It seems, therefore, that the greater the amount of cold working the more difficult it is to get rid of the internal stress completely by the annealing.

Next, the increase of the density between the states C and D is, according to the writer's view, due mostly to the vanishing of the minute cavities present in the metal at the C state, though a small part of the increase may be caused by the complete removal of the internal stress. Therefore, the decrease of the density between the states B and C is due mostly to the production of the minute cavities. The fact that the value of density returns almost to the value at the state B by annealing at 900°C or more seems to be in accord with the above view. As seen in Fig. 5, by the cold rolling to about 60% the density of the specimens (m) and (n), both at the state C initially,

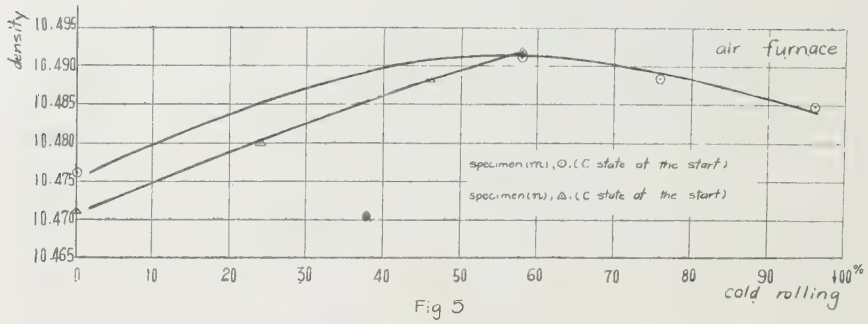


Fig 5

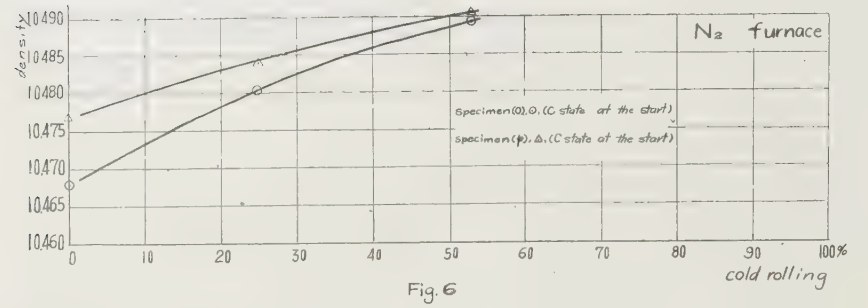


Fig. 6

approaches the B value, but does not coincide with that value. This seems to be caused by a small decrease of the density due to the increased internal stress produced by the cold rolling; and the value of the density thus obtained nearly coincides with the value at the state A. Similarly, as is seen in Fig. 6, the densities of the specimens (o) and (p) approach and come to the value of the state A by the process of successive cold rollings. From these facts it seems rather evident that nearly all the minute cavities can be vanished by cold rolling to about 60%. This fact can also be ascertained by the auxiliary experiments mentioned later. Still more, the necessity of about 60% cold rolling to vanish almost all the minute cavities seems to be inferable from Figs. 7 and 8.

Next let us consider again the state D. According to U. Yoshida and K. Koyanagi,[1] metal crystals having some distortion melt at their boundaries even at the temperatures below the melting point of the metal. This was confirmed by the writer from the fact that when two silver plates held tightly together were annealed at about 700°C for a long time they adhered together so strongly that it was a little

1. These Memoirs, **18** (1935).

difficult to separate them with the hands. When the minute cavities possessed by the specimens at the state C were heated at a higher temperature, they were filled gradually with the melted metal; and thus when the specimen cooled and contracted as a whole, its density became greater than in the state C. Therefore the rise between the points C and D in an ideal case is to recover or to exceed the value at the state B, as is seen in the specimens (d) and (e) in Fig. 2, which were annealed in a vacuum furnace.

When the specimens devoid of the cavities at the D state are subjected to successive cold rollings, they show successive decreases

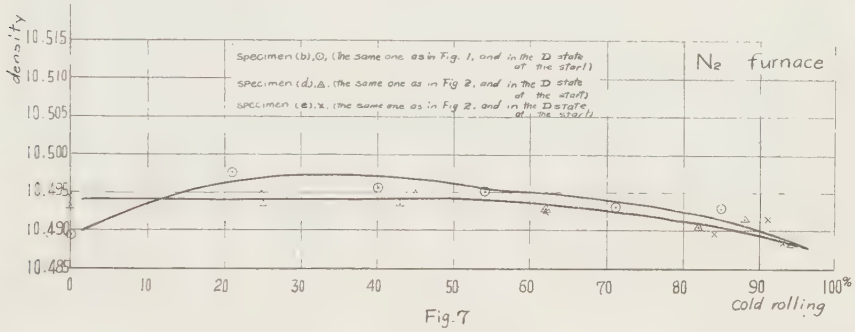


Fig. 7

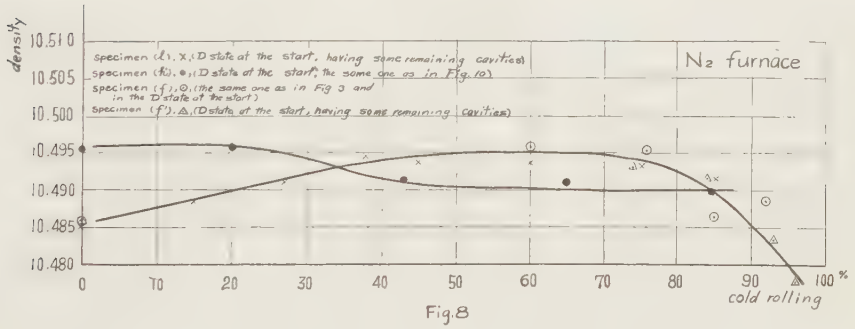


Fig. 8

of density as is seen in the specimens (d) and (e) in Fig. 7 and (h′) in Fig. 8. When the specimens (b) in Fig. 1 and (f) in Fig. 3, which seem to have some remaining cavities at the state D, are subjected to successive cold rollings, their densities increase gradually at first, depending on the amount of the cold rollings. As is seen from the curves corresponding to the specimens (b) in Fig. 7 and (f) in Fig. 8, the maximum densities of the specimens approach that at the B state.

The results obtained by giving successive annealings to the several specimens which were at the D state and cold rolled differently are

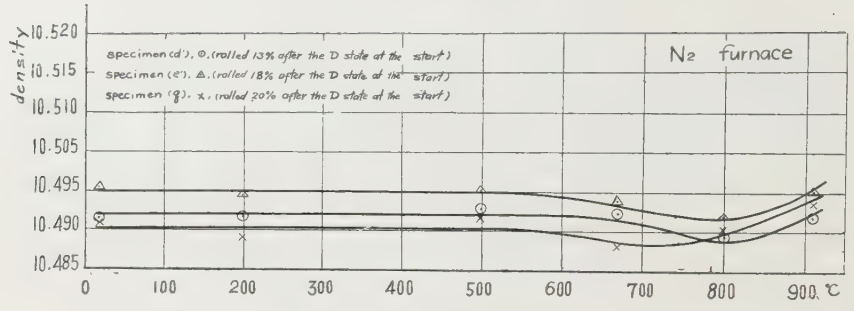

density
10.520
10.515
10.510
10.505
10.495
10.490
10.485
specimen (d'), ⊙, (rolled 13% after the D state at the start)
specimen (e'), △, (rolled 18% after the D state at the start)
specimen (g), ×, (rolled 20% after the D state at the start)
N₂ furnace
0 100 200 300 400 500 600 700 800 900 °C
temperature of annealing

Fig. 9

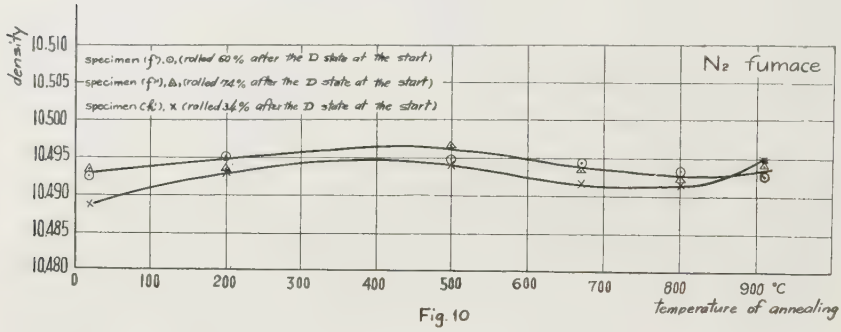

density
10.510
10.505
10.500
10.495
10.490
10.485
10.480
specimen (f'), ⊙, (rolled 60% after the D state at the start)
specimen (f''), △, (rolled 74% after the D state at the start)
specimen (h'), ×, (rolled 34% after the D state at the start)
N₂ furnace
0 100 200 300 400 500 600 700 800 900 °C
temperature of annealing

Fig. 10

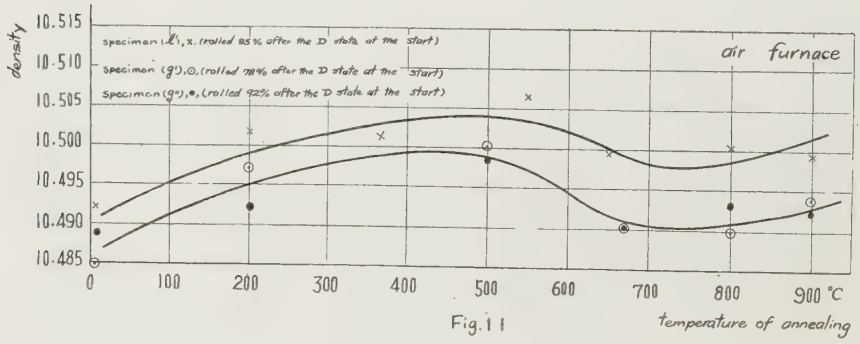

density
10.515
10.510
10.505
10.500
10.495
10.490
10.485
specimen (i'), ×, (rolled 85% after the D state at the start)
specimen (g''), ⊙, (rolled 78% after the D state at the start)
specimen (g''), ●, (rolled 92% after the D state at the start)
air furnace
0 100 200 300 400 500 600 700 800 900 °C
temperature of annealing

Fig. 11

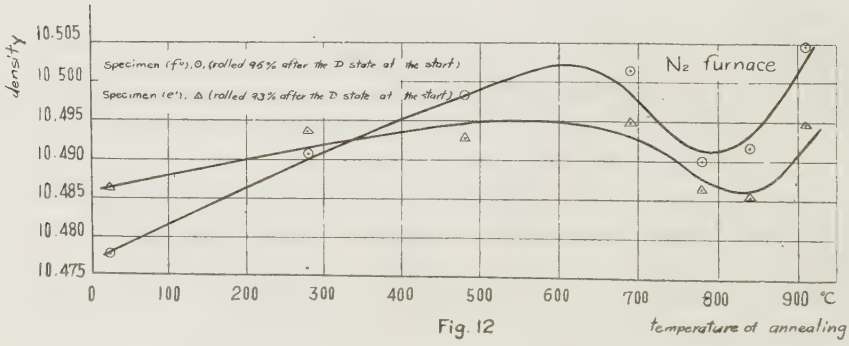


Fig. 12

shown in Figs. 9, 10, 11 and 12. With the specimens subjected to the rollings below 30% the rise of the density caused by the release of the stress could not be detected and the decrease of the density caused by the production of the cavities was not remarkable. With the specimens which were rolled within the range of about 40%–70%, the release of the stress occurred at about 400°C, and the difference between the A and B values was about $5/10^4$ of the density. With the specimens which were rolled very strongly to about 80% or 90%, the release of the stress took place at the annealing temperature of about 500°C–600°C, and the decrease of the density at the C state was about $1/10^3$ of the density, as is seen in Fig. 12.

According to Fig. 12, where strongly worked specimens were annealed, the recovery to the B value by annealing was almost perfect. Judging from this, it seems almost certain that the cavities were not formed by the process of rolling. The amount of the decrease in the density which was caused by the production of the cavities differed according to the temperature at the B state and the history, especially the degree of cold working before the recrystallization.

From the experiments described above the manner of the change of the density of silver with the annealing and the cold rolling has now become very clear. As an example, the behavior of the density of the specimen (f), when it is subjected to the process of annealing and cold rolling alternately, is represented by the upper curve in Fig. 13. This curve seems to clarify the way to get the standard value of the density of a specimen of silver. Let the specimen arrive at

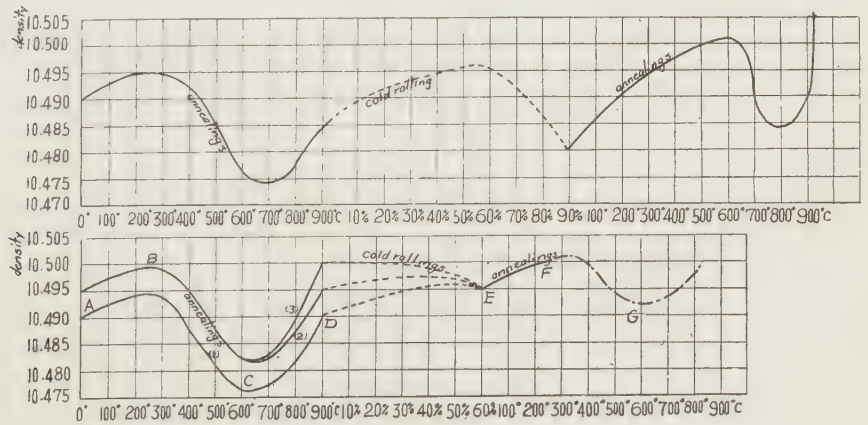


Fig. 13

the state D by passing through the path A B C D by successive annealings. This D state is not necessarily entirely devoid of minute cavities and a subsequent cold rolling to about 60% is to be done to destroy all the remaining cavities. The resulting internal stress is next to be released by the annealing at about 250°C, without forming any new minute cavities. Three curves drawn in the lower half of Fig. 13 show the values of the densities of three different specimens at various stages of such procedure of obtaining the standard value of the density. Among these three specimens, the one corresponding to the curve (1) seems to have had some cavities at first, as is revealed by a somewhat lower value of its density at the state B, and the other two corresponding to the curves (2) and (3) seem to have had almost no cavities at first, as is shown by the higher value of their densities at the B state which is almost the same as that at the state F. Irrespective of such differences in the porosity at the start their densities become the same at and after the state E, by the vanishing of the remaining cavities in the process of rolling; and by the subsequent annealing at about 250°C the density of all the specimens arrives at the standard value at the state F. The value of the density thus obtained with these three specimens at the standard state F is 10.502 at 17°C.

The present research has explained systematically the rather irregular changes in the density of a metal by the process of annealing and cold working.

In conclusion the writer expresses his sincere thanks to Professor U. Yoshida of the Kyoto Imperial University by whose kind suggestions and encouragement the present research was carried out.

An Examination of the Imperfection of Aluminium Crystals

By **Masaharu Kabata**

(Received Sept. 18, 1936)

Abstract

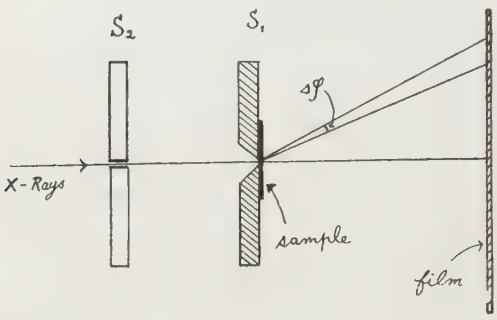
The imperfection of thin aluminium crystal was examined by means of convergent X-rays. The writer could never observe the formation of a perfect single crystal by the stress-annealing method. The axis of small rotation of the crystal fragments was always [211], and the amount of rotation ranged from 20′ to 30′.

Some years ago T. Fujiwara[1] devised a method for examining a crystal with convergent X-rays, and used this method to detect the imperfection of a tungsten crystal.[2] After him K. Tanaka[3] detected the manner of imperfection of a selenium crystal by the same method. This method is especially suitable for finding small inclinations between small crystal fragments when a crystal is composed of such small fragments. In the present experiment the writer applied this method in examining the perfections of thin aluminium crystals prepared by the stress-annealing method which uses K radiation of molybdenum. In this test the specimen was illuminated by the X-rays starting from various points on the surface of the target. Therefore characteristic X-rays having a suitable inclination for a given atomic plane of the crystal are reflected as their spectral lines on the photographic film. When the portion of the specimen which is illuminated by the X-rays is an entirely perfect single crystal, the spectral lines thus obtained are, of course, two doublets of K_α and K_β rays; but if the crystal is imperfect, and is composed of a few crystal fragments which have nearly the same but a little different orientation, then the spectral lines separate into several components. This method is very sensitive in such an examination, and even a slight imperfection of the crystal which can not be detected by the ordinary Laue-spots, can be brought to light very clearly, as is shown by Figs. 1 and 2, in Plate I. Fig. 1 shows the Laue-spots of a portion of an aluminium crystal and Fig.

1. T. Fujiwara: These Memoirs **11**, 283 (1928).
2. T. Fujiwara: These Memoirs **13**, 149 (1930).
3. K. Tanaka: These Memoirs **17**, 59 (1934).

2 is the photograph taken by illuminating the same portion of the crystal with convergent X-rays. In order to obtain sharp components of the spectral lines, the writer used a conical slit with an opening of 0.1 mm, and the specimen of an aluminium plate 0.1 mm in thickness, which was composed of a single crystal. In taking a photograph, the specimen was first illuminated by convergent X-rays, the central portion of the photographic film being protected from the direct X-rays with a small lead patch placed just in front of it; and then the image of the direct X-rays normal to the photographic film was impressed on this film by inserting a pin hole slit (S_2) with an opening of 0.3 mm at a predeterminate position in front of the conical slit (S_1), and by taking off the small patch in front of the film. Thus, by knowing the position of the direct X-rays which strike the film normally, the determination of the indices of the atomic planes which caused the spectral lines and the diffused Laue-spots is very much facilitated. As is seen in Fig. 2, Plate I, the same spectral lines appearing in a diffused Laue-spot consists of many sharp components. The aspect of such components is enlarged and reproduced in Fig. 3, Plate I. The distance between the components and the central spot, and the mutual distances between the components were accurately measured by Hilger's travelling micrometer. The indices of the atomic planes which caused the spectral lines were easily determined by the help of the crystallographic globe[1], from the positions of the direct X-rays, Laue-spots and the spectral lines.

Fig. 1



Now let the distance between the central spot and a component of the spectral lines be D, and the distance between the sample and the photographic film be D', then we can find the angle φ between the X-rays which is due to the said component, and the direct X-rays which strike the film normally by $\tan\varphi=\frac{D}{D'}$. Thus by know-

1. U. Yoshida: Jap. Journ. Physics, **4**, 133 (1927); and S. Takeyama: These Mem., **12**, 257 (1929).

ing the values of φ for every component, $\Delta\varphi$ the difference in the values of φ can be found immediately for any pair of the components. Every one of these components must belong to any one of the components which belong to the K_α and K_β doublets. The performance of this designation is of first importance.

From Bragg's equation $2d_{hkl}\sin\theta=\lambda$, the value of d_{hkl} being known as an atomic plane of known indices, the values of θ_{α_2}, θ_{α_1} and θ_{β_1} are obtained by giving the known values of the wave length of K_{α_2}, K_{α_1} and K_{β_1} lines of molybdenum respectively. The values of $\theta_{\alpha_2}-\theta_{\alpha_1}$ and $\theta_{\alpha_1}-\theta_{\beta_1}$ thus calculated are shown in Table I for various atomic planes. As the intensity of the K_{β_2} component was so weak that this component did not appear on the film in the present case, it was omitted in the table. By comparing the values of $\theta_{\alpha_2}-\theta_{\alpha_1}$ and $\theta_{\alpha_1}-\theta_{\beta_1}$ with those $\Delta\varphi$ obtained for various pairs of the component lines appearing on the film, we can choose a set of the component lines as the spectrum of K_{α_2}, K_{α_1} and K_{β_1} lines which are caused by the same crystal fragment of aluminium. Thus when the position of the aluminium crystal which is illuminated by the X-rays consists of two or more crystal fragments oriented a little differently, we obtain a corresponding number of the sets of the spectral lines of K_{α_2}, K_{α_1} and K_{β_1}. When this classification is made, the value of $\Delta\varphi$ between two component lines which are caused by two crystal fragments oriented a little differently and both belonging to one of any of the spectral lines K_{α_2}, K_{α_1} and K_{β_1}, immediately gives the inclination between the corresponding atomic planes of the two crystal fragments. When more than two sets of the spectral components which are caused by different atomic planes of the crystal are impressed on the same photographic film with the same portion of the specimen, we can obtain the amount of rotation of two crystal fragments as a whole, from the inclinations between the corresponding atomic planes belonging to different crystal fragments. This was very easily done with the aid of the crystallographic globe. The results obtained with four different specimens are tabulated in the tables from Table II to Table V.

Table I

Indices	$\theta_{\alpha_2}-\theta_{\alpha_1}$	$\theta_{\alpha_1}-\theta_{\beta_1}$
120	5′ 20″	1° 21′ 53″
311	7 22	1 52 54
331	10 2	2 32 59
511	12 36	3 8 27

In these tables the first column gives the indices of the atomic planes, the second column the distances between the central spot and

Table II

Indices	D mm	φ	Kind of spectral lines		Inclination between the same atomic planes
331	34.30	44° 25′ 20″	α_2		10′ 20″
	34.10	44 15 20	α_1		
	34.09	44 15 0		α_2	
	33.90	44 4 50		α_1	
	31.19	41 42 20	β_1		
	31.00	41 31 50		β_1	
511	48.72	54° 18′ 10″	α_2		10′ 0″
	48.42	54 8 10		α_2	
	48.34	54 5 40	α_1		
	48.05	53 55 40		α_1	
210	39.86	48° 42′ 50″	α_2		16′ 10″
	39.75	48 38 0	α_1	α_2	
	39.48	48 26 40		α_1	
	39.37	48 21 50			

Table III

Indices	D mm	φ	Kind of spectral lines		Inclination between the same atomic planes
331	29.55	44° 34′ 0″	α_2		13′ 40″
	29.38	44 24 0	α_1		
	29.32	44 20 30		α_2	
	29.15	44 10 20		α_1	
	26.87	41 51 0	β_1		
	26.66	41 37 20		β_1	
511	42.19	54° 33′ 50″	α_2		11′ 40″
	41.86	54 22 20		α_2	
	41.83	54 21 20	α_1		
	41.54	54 9 40		α_1	
210	34.55	49° 1′ 40″	α_2		17′ 30″
	34.45	48 56 50	α_1		
	34.19	48 44 10		α_2	
	34.09	48 39 20		α_1	

Table IV

Indices	D mm	φ	Kind of spectral lines			Inclination between the same atomic planes
115	56.90	62° 12′ 0″	α_2			10′ 30″
	56.53	62 1 40		α_2		
	56.36	61 59 30	α_1			
	55.99	51 49 0		α_1		
$33\bar{1}$	27.43	42° 26′ 0″	α_2			17′ 40″
	27.27	42 16 0	α_1			
	27.14	42 8 20		α_2		
	26.98	41 58 10		α_1		
	24.92	39 43 0	β_1			
	24.66	39 25 10		β_1		

Table IV (Continued)

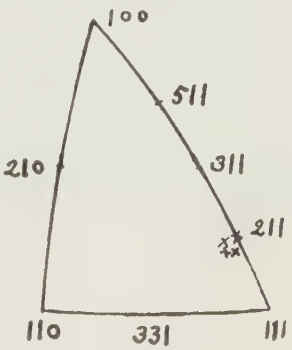
Indices	D mm	φ	Kind of spectral lines			Inclination between the same atomic planes
	38.03	51° 44′ 10″			α_2	
	37.83	51 35 20	α_2			8′ 40″
	37.75	51 31 30			α_1	
$15\bar{1}$	37.55	51 22 40	α_1			13′ 10″
	37.54	51 22 10		α_2		
	37.26	51 9 40		α_1		
	33.77	48 23 0			β_1	
	33.58	48 13 10	β_1			8′ 50″

Table V

Indices	D mm	φ	Kind of spectral lines			Inclination between the same atomic planes
	45.62	63° 14′ 40″	α_2			
115	45.21	63 2 0	α_1			15′ 40″
	45.11	62 59 0		α_2		
	44.70	62 46 20		α_1		
	21.19	42° 39′ 30″	α_2			
	21.07	42 29 30	α_1			20′ 40″
$33\bar{1}$	20.94	42 18 50		α_2		
	20.82	42 8 40		α_1		20′ 50″
	19.26	39 56 30	β_1			
	19.02	39 35 40		β_1		20′ 50″
	29.33	51° 54′ 0″			α_2	
	29.27	51 50 0	α_1			
	29.11	51 41 20			α_1	8′ 40″
$15\bar{1}$	29.07	51 39 10		α_2		14′ 40″
	28.86	51 26 40		α_1		
	26.18	48 41 40	β_1			
	26.04	48 33 0			β_1	8′ 40″

the spectral lines, the third column the values of φ, the fourth column the designation of the spectral lines, the fifth column the angle between two corresponding atomic planes which belong to different crystal fragments. Here it must be noted that the spectral lines belonging to a given crystal fragment are tabulated in the same subcolumn in the fourth column. The axis of small rotation of the crystal fragments is obtained in the manner stated before, and the results obtained with four different specimens are represented in Fig. 2 as a stereographic projection. From this figure, it is seen clearly that the axis of small rotation of

Fig. 2



the crystal fragments of aluminium is always [211] as far as the present experiment is concerned.

This axis seems to have a special significance in a crystal composed of the face centred cubic lattice, because this axis has also been found to be the axis of the fibrous arrangement in the case of rolled platinum foil[1] and of a compressed aluminium plate.[2] The angle of rotation of the crystal fragments around this is tabulated in Table VI.

Table VI

No. of the specimen	No. 1	No. 2	No. 3	No. 4
Angle of rotation	24′	28′	20′	24′

The angle of such rotation is not always the same and ranges from about 20′ to about 30′. In all the writer's experiments with thin specimens of aluminium about 0.1 mm thick, an entirely perfect single crystal has never been observed.

In conclusion the writer wishes to express his sincere thanks to Prof. U. Yoshida and Dr. K. Tanaka for their kind guidance and suggestions.

1. S. Tanaka: These Memoirs **8**, 319 (1925).
2. Y. Fukami: These Memoirs **15**, 23 (1932).

Plate I

Fig. 1

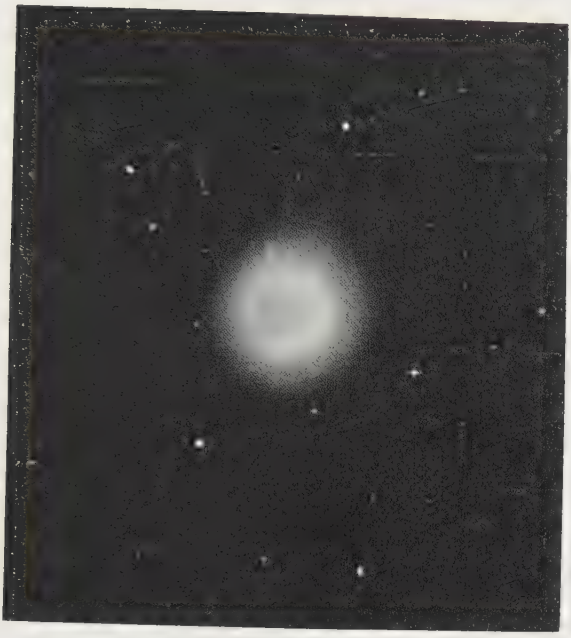


Fig. 2

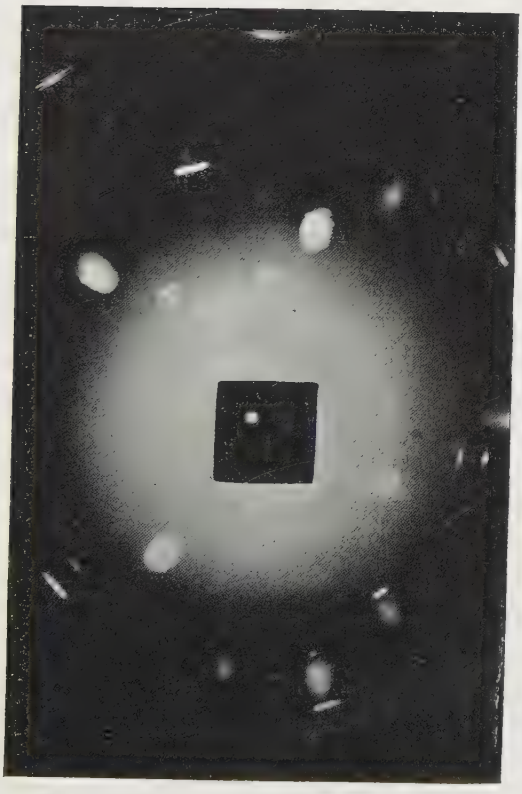
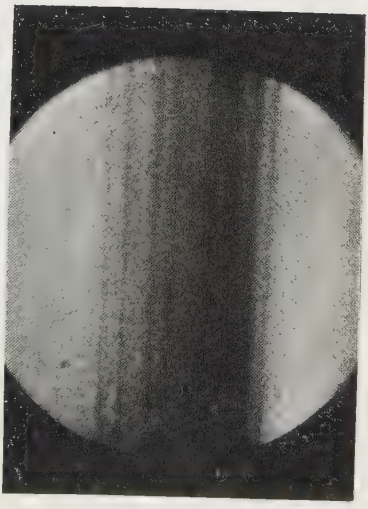


Fig. 3



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The Thickness of Silver Chloride Film Produced on the Surface of Silver Plate

By Shin'ichi Shimadzu

(Received Sept. 18, 1936)

Abstract

A powder X-ray photograph taken of a silver plate coated with silver chloride film which is produced by dipping the plate into chlorine water, contains Debye-Scherrer rings of silver and silver chloride. The thickness of the film can be measured by comparing the intensities of the rings of both substances. The present experiment was made to learn how the thickness changes with the concentration of the chlorine water, its temperature, and the duration of the time of dipping the plate.

(1) Measurement of the thickness of silver chloride film

In the present experiment the writer used the same method as in the case of the contamination on the surface of lead plate, which results have already been published.[1] The intensity of the X-rays reflected by a thin sample of x cms. thickness is given by the equation

$$I_1 = KI_0F^2\lambda^3\frac{N^2}{\mu}j\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}\left(1-e^{-2\mu x\frac{1}{\sin\theta}}\right) \qquad (1)$$

when its surface makes an angle θ with the incident beam. Here λ is the wave length of the X-rays, K a constant, I_0 the intensity of the primary X-rays, N the number of the unit cells in a unit volume, μ the absorption coefficient of the sample for the X-rays, j the number of the like faces of the crystal which contribute to a single reflection, θ the glancing angle which satisfies Bragg's equation, and F is the structure amplitude. The value of F for silver and silver chloride are given as follows when the indices of the atomic plane are (hkl):

Ag: h, k, l are all even or all odd	$F=4\overline{\mathrm{Ag}}$
the other cases	$F=0$
AgCl: h, k, l are all even	$F=4(\overline{\mathrm{Ag}}+\overline{\mathrm{Cl}})$
h, k, l are all odd	$F=4(\overline{\mathrm{Ag}}-\overline{\mathrm{Cl}})$
the other cases	$F=0$.

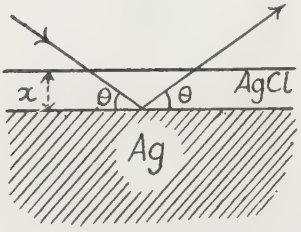
$\overline{\mathrm{Ag}}$ and $\overline{\mathrm{Cl}}$ indicate the scattering powers of silver and chlorine atoms respectively.

1. These Memoirs, **17**, 79 (1934)

When the thickness x tends to infinity, expression (1) becomes identical with that of an ordinary powder photograph, that is

$$I' = KI_0F^2\lambda^3\frac{N^2}{\mu}j\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}. \qquad (2)$$

Fig. 1



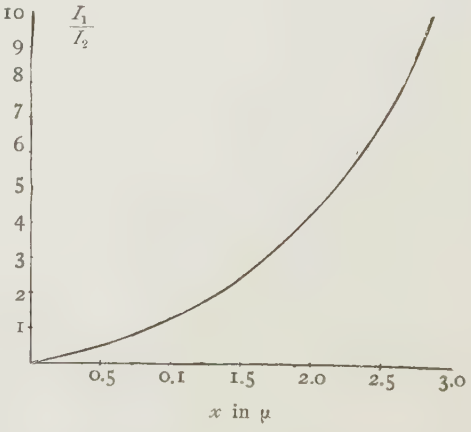
If we ap ply expression (2) to the case of silver plate, I' gives the intensity of X-rays reflected by the silver plate when there is no film on its surface. When there is a silver chloride film on the surface of the plate and the thickness of the film which X-rays have to pass through is $2x/\sin\theta$ as shown in Fig. 1, then the intensity of X-rays reflected by the silver plate is given by

$$I_2 = I'e^{-2\mu x\frac{1}{\sin\theta}}$$

$$= KI_0F^2\lambda^3\frac{N^2}{\mu}j\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}e^{-2\mu x\frac{1}{\sin\theta}}. \qquad (3)$$

If we apply expression (1) to an atomic plane of silver chloride and expression (3) to an atomic plane of silver plate for the same value of x, then I_1 and I_2 give respectively the intensities of X-rays reflected by these atomic planes of the silver chloride film and of the silver plate. Therefore if we find the ratio of these intensities, we can ascertain the value of the thickness of the silver chloride layer.

Fig. 2



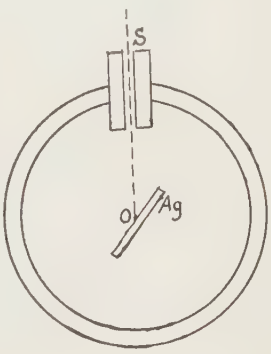
The writer chose the atomic planes (200) for silver and (220) for silver chloride respectively, because the X-rays reflected by these planes were very intense and their spectral lines were situated close to each other. The ratio I_1/I_2 for various values of x is calculated with the expressions (1) and (3) by giving known values for the constants. The relation between I_1/I_2 and x is plotted in the curve shown in Fig. 2. By means of this curve the value of x is obtained when the value of I_1/I_2 is found experimentally. This value of I_1/I_2 was obtained in the

present experiment by measuring the relative intensities of the spectral lines on the photographic film with a standard optical wedge.

(2) Experiment

The camera employed in the present experiment was cylindrical in shape as shown in Fig. 3, and a photographic film was laid along its inner surface. In the figure, S is the slit, Ag the sample of silver plate and O is the position of the axis of the cylinder. The silver plate was so placed that its surface which was to be examined occupied exactly the position of the axis of the cylinder; and the thickness of the chloride layer through which the X-rays reflected by the atomic plane (200) of silver had to pass was just $2x/\sin\theta$ as shown in Fig. 1. The X-rays used in the present experiment were K radiations starting from an iron target.

Fig. 3



To prepare the samples the writer dipped the silver plates into a three litre flask of chlorine water, the neck of which was narrow and long. The flask was filled with chlorine water up to its neck; thus by making the contacting surface of the chlorine water and air very small, the escaping of the chlorine gas and consequently the change of its concentration was greatly minimized. The temperature of the chlorine water was kept constant by immersing the flask in a water bath of large volume.

As soon as the silver plate was coated with a thin silver chloride film, its surface became violet coloured instead of white, which colour is peculiar to silver chloride. This was probably due to the separation of metallic silver from silver chloride upon exposure to light. In order to estimate the influence of the presence of such metallic silver, the writer examined by K radiations of iron a free thin film of the silver chloride which was obtained from the surface of a silver anode, on which it was formed by electrolysis in a hydrochloric acid solution. In spite of the separation of the metallic silver on both sides of the film in this case by the action of light, there were no rings of silver in the photograph. Thus it may be concluded that the quantity of silver separated by light is so small that it has no influence upon the measurement of the thickness of the film.

The values of the thickness gained by the above method was compared with those determined by weighing. For this purpose a silver plate of 32 mm. in length, 25 mm. in width and 0.5 mm. in thickness was weighed. Next, this plate was coated with silver chloride film by dipping it into chlorine water, and an X-ray diffraction photograph of it was taken. Lastly, it was weighed to find the weight of the chlorine combined with silver. From this weight and the chemical equation $Ag_2+Cl_2=2AgCl$, the weight of silver chloride produced in this case was calculated. Moreover, by weighing the silver plate after dissolving the silver chloride in ammonia water, the weight of silver chloride was directly measured. As the values of the weight of the silver chloride obtained by these two methods closely coincided, the writer took the mean value as the value of the silver chloride. From this value, the specific gravity of silver chloride and the surface area of the silver plate, the thickness of the silver chloride film was calculated; and it was ascertained that the value of the thickness of the film thus obtained coincided well with that found by the X-ray method. This showed that the method of measuring the thickness of silver chloride film by comparing the intensities of the rings in the X-ray diffraction photograph was correct.

(3) Results

Pieces of silver plate 25 mm. long and 3 mm. wide were cut out from a large silver plate 0.5 mm. thick. These pieces were dipped into chlorine water of various temperatures and concentrations for various durations of time after their surfaces were cleaned. In the present experiment different chlorine waters, each containing 2.49 gr, 1.12 gr, 0.39 gr, 0.11 gr, and 0.06 gr of chlorine in one litre of water, were kept at the temperatures of 43°C, 25°C and 6°C. The specimens were dipped in all of these chlorine waters for various durations of time. The X-ray diffraction photographs were taken with each of these specimens. One series of such photographs are shown in Fig. 1 in Plate I, which were obtained with the samples prepared in chlorine water containing 1.12 gr of chlorine at 25°C.

By the method mentioned above the thickness of the silver chloride film was measured for each of the photographs thus obtained; and the relation between the thickness of the film and the time of the dipping of the silver plate are shown in Figs. 4a and 4b for various concentrations and temperatures of the chlorine water. The curves

drawn in these figures reveal that the rate of increase in the thickness of the silver chloride film is very rapid upon first dipping, then after a while suddenly lowers, scarcely rises for a certain interval, and at last rises again rather linearly with the time.

Judging from these curves, when the thickness of the silver chloride film attains a certain value, cracks arise here and there in the film, permitting the chlorine water to invade and touch the silver plate directly. This seems very clear from the fact that the size of the unit cell of silver chloride (cubic, lattice constant: 5.54Å) is larger than that of silver (cubic, lattice constant: 4.077Å), and that the

Fig. 4a

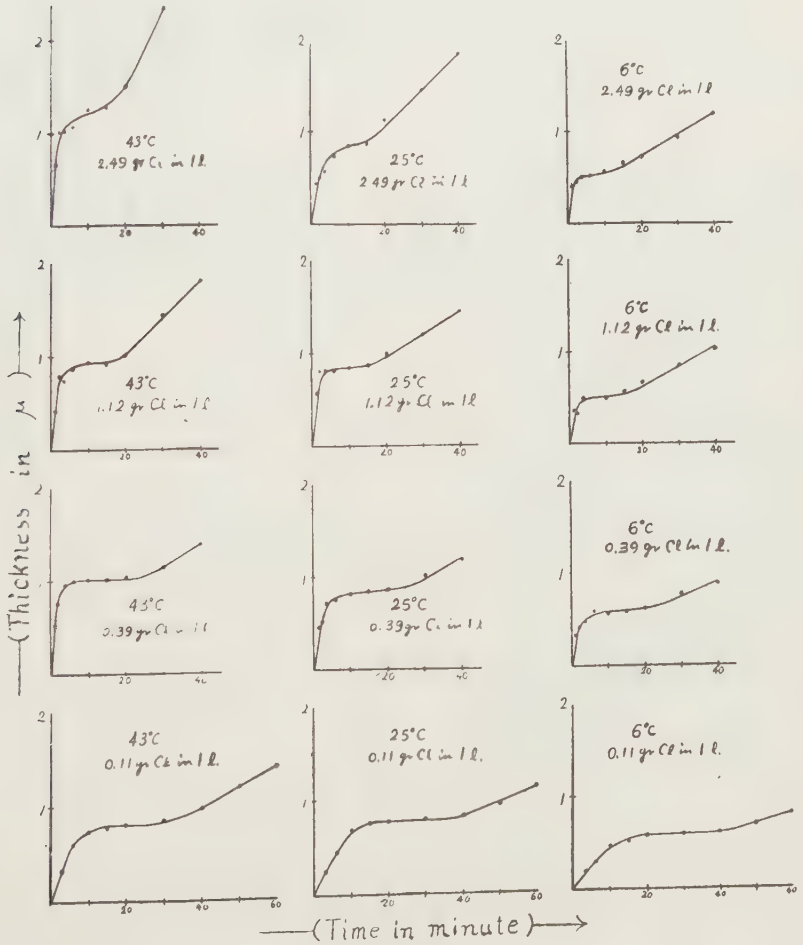
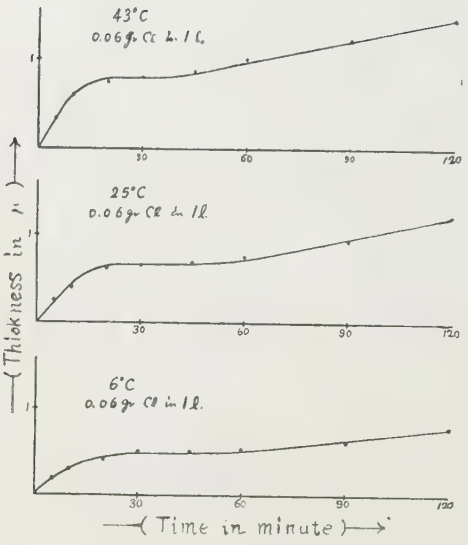


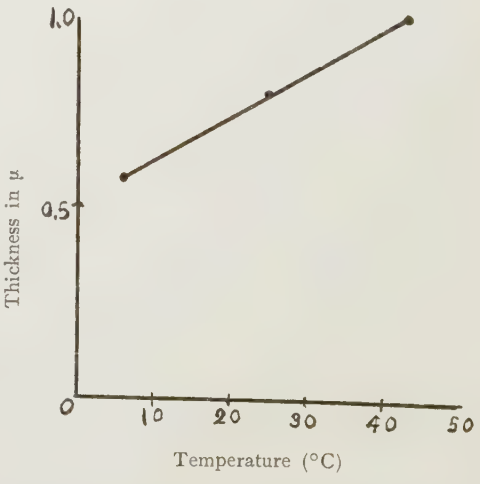
Fig. 4b



specific gravity of the former (5.56) is smaller than that of the latter (10.50).

Next, the thickness of the film at the part in the curves where it scarcely increases with the time, hardly depends upon the concentration of the chlorine water, but upon increases in the temperature, i. e., about 1μ at 43°C, 0.8μ at 25°C and 0.6μ at 6°C. This relation of the thickness with the temperature is shown in Fig. 5. In the part of the curves where the thickness increases linearly with time, the inclination of the line showing this linear relation becomes steeper with increase of the concentration and the temperature. If the inclination of such a straight line is indicated by $\tan\alpha$, where α is the angle between the line and the abscissa, then $\tan\alpha$ increases almost linearly with the concentration for a given temperature, and also increases similarly with the temperature for a given concentration, as is shown in Figs. 6 and 7.

Fig. 5



The writer examined the effect of the size of the crystal grains of silver upon the rate of increase in the thickness of silver chloride film. For this purpose the writer selected two silver plates consisting of crystal grains of different size: one fine-grained and the other coarse-grained. These silver plates were dipped separately in chlorine water containing 1.03 gr of

chlorine in one litre at 17°C for various durations of time. The size of the crystal grains of the silver plates were examined by X-rays: the fine-grained one was revealed by continuous diffraction rings on the photograph and the coarse-grained one by an assemblage of many distinct spots as shown in Figs. 2 and 3 in Plate I. The results of the experiment on these two samples are shown in Fig. 8; where curve A corresponds to the fine-grained one and curve B to the large-grained one. The general aspect of these two curves is entirely the same as those in Figs. 4a and 4b. The two curves A and B coincide almost entirely until the state is reached where the thickness of the chloride film increases linearly with time, but in this state the thickness of the film increases more rapidly with the fine-grained sample than with the large-grained one. This indicates that the larger the crystal grains of silver, the harder it is for the cracks to be formed in the chloride film.

Fig. 6

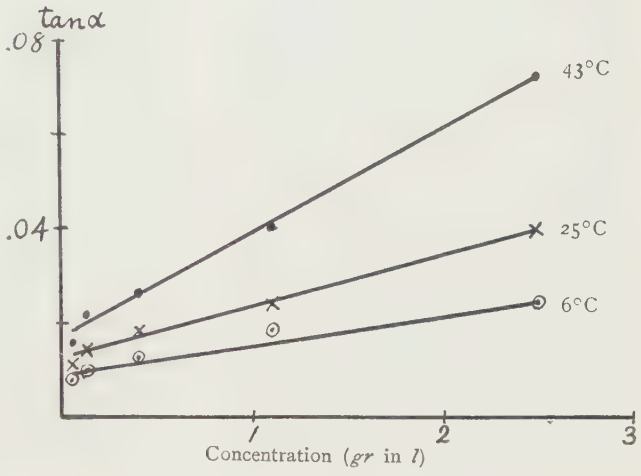
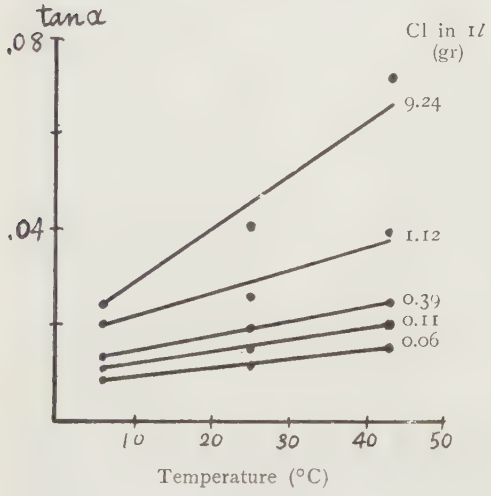
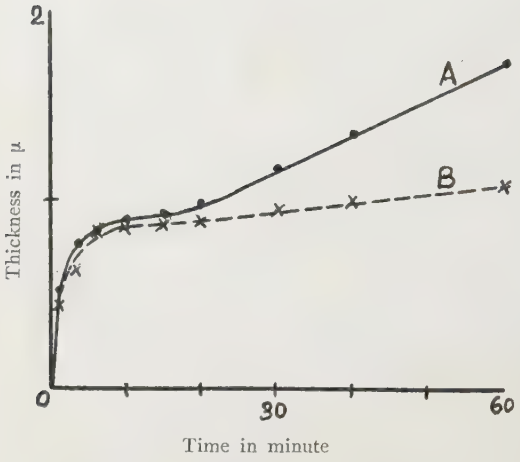


Fig. 7



As to the thickness of the chloride film formed when the silver plate is dipped in the chlorine water for a very long time, very probably

Fig. 8



it nearly attains a maximum value. But this is not clear yet, a further study on this point being now in progress.

In conclusion the writer wishes to express his sincere thanks to Prof. U. Yoshida for his kind guidance in the present research; and also to Prof. N. Sasaki of the Chemical Institute for his helpful suggestions in preparing the samples.

Plate I

Fig. 1

Ag (200) Ag Cl (220)

Fig. 2

Fig. 3

A Study of the Minor Fluctuation of the Atmospheric Pressure (V)

By **Tadao Namekawa**

(Received Sept. 18, 1936)

Part IV

T. Shida's Microbarograph

In 1913, Prof. Toshi Shida designed a new-type microbarograph. One of the features of his design was the avoidance of the use of a mechanical lever, which would inevitably have magnified the frictional force. However, when it was found that continued observances by the optical method were excessively expensive he sought to achieve his purpose by modifying the U-tube manometer. In order to increase its magnifying power, this manometer makes use of a U-tube of a special shape, its cross-sectional area being 1 : 10. One end of this U-tube is exposed to the atmosphere, while the other end is pneumatically connected with a closed air reservoir, which contains a volume of about 1 m^3 and is buried under ground so as to be kept free from temperature changes. In order that the flow and reflow of the liquid in the U-tube corresponding to the change of atmospheric pressure may be self-recorded, liquid paraffin of the specific gravity of about 0.9 is poured into the upper exposed end of the U-tube and water is placed in the other end of the tube, a float being hung on the boundary surface of the liquids. This hanging float is connected with the counter balance by means of fine platinum wire that runs through a frictional pulley. A recording pen is hung in the middle of the platinum wire and balanced between the two pulleys. As the pen on the connecting wire can be changed to any position, the zero point on the recorder can be located according to the observers' requirement. Thus the flow and reflow of the liquids in the U-tube corresponding to pressure changes appear as the fluctuation of the boundary surface of the working liquids, and the hanging float moves up and down to attain equilibrium under the influence of the force of buoyancy due to the difference in density of the two liquids. This up and down motion is self-recorded by the pen on the smoked paper.

The recorder employed is so arranged as to rotate at the rate of about 1 mm. per minute. Moreover, in order to register time accurately, a time-ticker is attached to the recorder. This time-ticker consists of a clock, a coil, and a magnetic bar serving also as a counter balance. In constructing this instrument, Prof. Shida took into consideration various factors: the magnification, the frictional force, the outlook of the apparatus, the selection of the two working liquids, the undesirable fact that the liquids in touch with the boundary of the float and the wall of the U-tube form a meniscus on account of surface tension. After he had thoroughly inquired into these points, he constructed, in 1918, a microbarograph of improved type as shown in Fig. 1.

Fig. 1

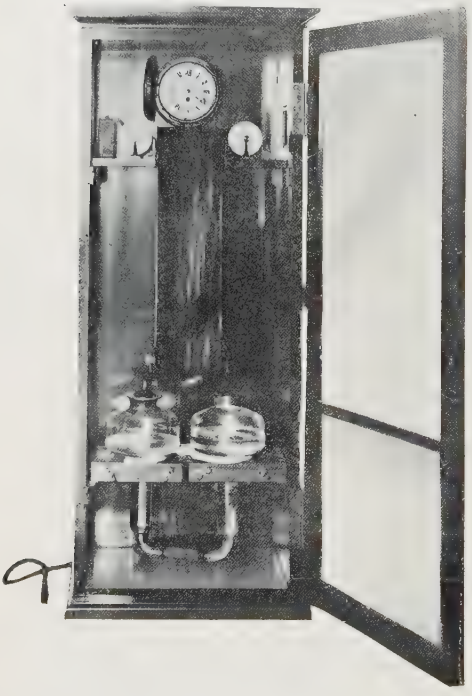
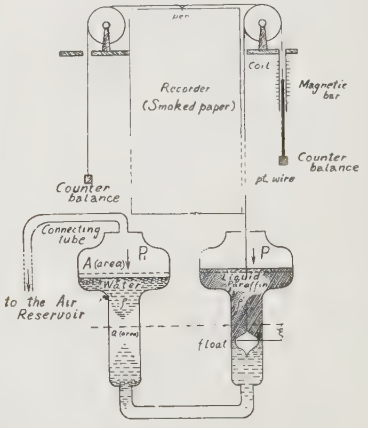


Fig. 2



Thereafter observation commenced by means of this instrument. The improved type microbarograph is shown diagramatically in Fig. 2. The exact constants of our working instrument are as follows:

$a = 52.6$ sq. cm. $\quad k = a/A = 0.091$

$\rho = 1.00 \quad \rho' = 0.87$

$V_0 = 1.0688$ m^3.

(*See Fig.* 2.)

This instrument is constructed to observe barometric fluctuations with periods, from a few minutes to half an hour, and the time scale is

also selected to serve the purpose. The free period of vibration of the recording part, consisting of a liquid column, a float, and a counter-balance, is about 7 sec., so that, in case of barometric fluctuations of comparatively longer periods, the correct result can be obtained by calculating the magnifying power of the instrument through statical treatment. Very rapid fluctuations of pressure are conveniently eliminated by the viscosity of the liquid paraffin in case of comparatively slow fluctuations of pressure, the air in the reservoir undergoes isothermal changes, and, when there is no leakage from the reservoir, the magnifying power of the instrument may be given in the following equation:

$$m = d\xi/dp = 1/(S + P_0 a/V_0)$$

where $S \equiv (\rho - \rho') + k(\rho + \rho')$ and $P_0 = 760$ mm. Hg.

And, because, with our instrument,

$$S + P_0 a/V_0 \fallingdotseq 0.351 \text{ (gr.)}$$

therefore dp (in mb.) $= 0.0344 d\xi$ (in mm. on record),

dp (in mm. Hg.) $= 0.0258 d\xi$ (in mm. on record).

In other words, the magnifying power is about 40 times (compared with mm. Hg.).

In actual use, a small leakage was given to the air reservoir, as is always the case with microbarographs of other types when they are in use. It is possible, by means of this leakage, to keep the recording pen within suitable limits on the paper, and to render the instrument independent of slow variations of temperature. The theory of microbarographs of this type is very simple. The leakage is assumed, as usual, to be $n(p - p')\sigma$, where $p - p'$ is the difference between the external and internal pressures, σ is the density of air, and n is the "coefficient of leakage." Now, assuming p and τ to be small deviations from the normal values (P_0, T_0) respectively of the external pressure and the temperature in the air reservoir, and neglecting small quantities, we get approximately

$$\frac{dp}{dt} = \left(\frac{aP_0}{V_0} + S\right)\frac{d\xi}{dt} + \frac{nSP_0\xi}{V_0} + \frac{P_0}{T_0}\frac{d\tau}{dt}.$$

This is the fundamental equation for the analysis of our microbarograms. $\frac{P_0}{T_0}\frac{d\tau}{dt}$ is a term depending on the temperature change in the reservoir, and, if it exists, we get a false record by the microbarograph. But it was ascertained, by actual observation of the temperature in the air reservoir, to be negligibly small. A small slow variation amounting to 0.1°C. per day exists, indeed, but a variation

of this extent causes no inconvenience. The coefficient of leakage can be determined by blowing air into the reservoir when $dp/dt \fallingdotseq 0$, and by calculating the rate at which the recording pen returns to its original position.

$$n = \frac{f}{l}\,\frac{\log\xi_0 - \log\xi}{t}, \qquad \left[\begin{array}{c} where\ f \equiv aP_0/V_0 + S \fallingdotseq 0.351\,g \\ l \equiv SP_0/V_0 \fallingdotseq 0.285\,g \end{array}\right].$$

$$\fallingdotseq 2.83\,\frac{\log_{10}\xi_0 - \log_{10}\xi}{t}$$

(t *in sec.*)

In our case, approximately $n = 4 \times 10^{-4}$ (*C. G. S.*).

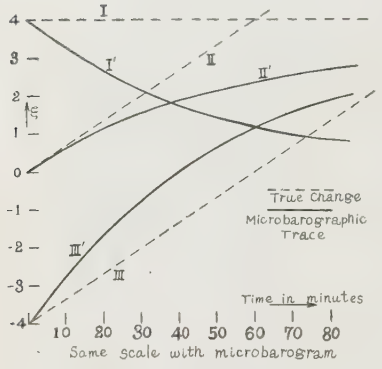
Adopting this n,

(i) $\dfrac{dp}{dt} = 0$, and $\xi_0 = 40$ mm. at $t = 0$ (*Curves of leakage*),

(ii) $p = ct$, and $\xi_0 = 0$ at $t = 0$,

(iii) $p = ct$, and $\xi_0 = -40$ mm. at $t = 0$.

Fig 3



The comparison between the actual pressure change and the microbarographic trace in these cases is shown in Fig. 3. Thus, the general aspect of the effect of leakage upon our microbarograph is made clear.

In case of waves of pressure with periods ranging from a few minutes to half an hour, such small leakages have no serious effect upon the amplitude and phase. Table I gives information concerning this point.

Table I

Period in min.	A'/A	ϵ	
		in degrees	in minutes
5	1.000	0.88	0.01
10	0.999	1.72	0.05
15	0.999	2.67	0.11
20	0.998	3.57	0.20
30	0.995	5.33	0.45
60	0.979	10.53	1.76

$p = A\sin\frac{2\pi}{T}t$: True change

$p' = A'\sin\left(\frac{2\pi}{T}t + \epsilon\right)$: Corresponding recorded change

Table II

No.	Max.	Min.
I	$-0.4^{\text{min.}}$	$+0.3^{\text{min.}}$
II	-0.3	$+0.3$
III	-0.2	$+0.2$
IV	-0.2	$+0.2$
V	-0.1	$+0.1$

But, when there is noteworthy initial displacement, curves of leakage superpose on periodic changes, and apparent maximum and minimum phases

show its influences. In Table 2 is shown an instance, where $n=4\times 10^{-4}$, $T=10$ min., $\xi_0=40$ mm., and amplitude of waves of pressure on record is 5 mm. When ξ is large, phase differences to the extent of 0.3 min. are found, but the smaller the value of ξ, the smaller becomes the difference. However, in case of apparent phase difference, this effect disappears, when the curves of leakage is eliminated from the observed curves.

Acknowledgements

Prof. Toshi Shida, in charge of our Geophysical Institute at Kyoto, began in 1919 the microbarographical observation as one branch of his study. At the very beginning of the work, I was only an observer, engaged in helping him in the laboratory. After some time I was permitted to carry on the work as my own project. Meanwhile, the observations were continued through the assistance of the members of the observatories. When I was allowed to take charge of the teaching of meteorology, I assigned to students of geophysics and research students of meteorology, certain problems in connection with this study. Those students were:

R. Yamashita, K. Shiozaki, Y. Tamura, T. Murayama, E. Sakazaki, and T. Takahashi.

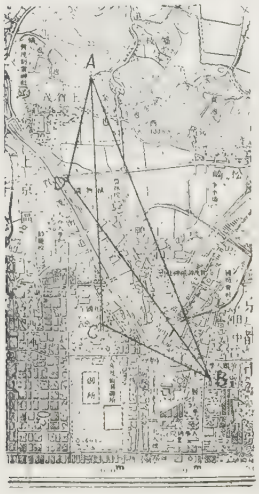
I take this opportunity to express my gratitude for their assistance which has been invaluable in conducting this research. Numerous unpublished notes and records of theirs have been put in order and incorporated into this paper. In the task of organizing these materials I was again ably assisted by Mr. T. Takahashi, and also by Mr. S. Aoki, who arranged tables of figures and drew diagrams for this publication. I likewise wish to thank the directors of the meteorological observatories of Japan, who have at my request kindly sent me valuable records and given me permission to reproduce them. Particularly do I wish to thank the director of the Central Meteorological Observatory of Japan who has given permission to reproduce numberless weather charts. I am indebted to Prof. T. Nomitsu for his kind encouragement during the process of my work and for his generosity in giving permission to reproduce the records of the tide-gauge in the Bay of Ôsaki. As for Prof. Shida, who gave me a chance to do this study and gave me leave to reproduce his numberless microbarograms, words cannot express my gratitude for his generosity and sympathy. Indeed, if it were not for his influential

support and his considerate guidance, it would have been impossible for me to accomplish this study.

Appendix

The Location of our Microbarographic Stations. (*See Fig. 4.*)

Fig. 4



A-Station:
Kamigamo Geophysical Observatory.

B-Station:
Geophysical Institute, Kyoto Imperial University.

C-Station:
Prof. T. Shida's Private House.

D-Station:
Meteorological Research Institute.

Corrigenda for "A Study of the Minor Fluctuation of the Atmospheric Pressure"

Part I. (Vol. XVII. No. 6. 1934)

Page	Line	Read	For
406	4 from the last (Eq. 2)	$p_0=R\rho_0\theta_0$	$P_0=R\rho_0\theta_0$
408	1.	If	It
408	The last (Eq. 14) 2nd term.	$\left\{\frac{dc^2}{dy}-\gamma g\right\}\frac{\partial\chi}{\partial y}$	$\left\{\frac{dc^2}{dy}-\gamma g\right\}\frac{\partial x}{\partial y}$
409	3 from the last (Eq. 18)	$\frac{\partial^2\chi}{\partial y^2}-2m\frac{\partial\chi}{\partial y}+\alpha^2\chi=0$	$\frac{\partial^2\chi}{\partial y^2}-2m\frac{\partial\chi}{\partial y}+\sigma^2\chi=0$
410	The last	(23)	(22)
411	12 from the last (Eq. 26) in { }	$\{\varkappa(V-U)^2\coth\varkappa H-g\}$	$\{\varkappa(V-U)^2\cosh\varkappa H-g\}$
412	7 (Eq. 30)	$\chi'_{y=0}=-\frac{ai\sigma(V-U')g^2}{c_0'^2V\{g-\varkappa'(V-U')^2\}}$	$\chi'_{y=0}=-\frac{ai\sigma(V-U')g}{c_0^2V\{g-\varkappa'(V-U')^2\}}$
412	10 from the last	$g^2\gg\varkappa^2(V-U)^4$ $g^2\gg\varkappa'^2(V-U')^4$	$g^2\gg\varkappa^2(V-U)^2$ $g^2\gg\varkappa'^2(V-U)^2$

Part I. (Vol. XVII. No. 6. 1934) (Continued)

Page	Line	Read	For
413	8 (Eq. 37)	$\frac{ac_h^2\rho_h\chi(V-U)^2}{c_0^2\sinh\chi H}e^{-mH}$	$\frac{ac_h^2\rho_h(V-U)^2}{c_0^2\sinh\chi H}e^{-mH}$
414	1	the second term	the first term
414	6	$k^2{}_{0r}=\frac{\sigma_0{}^2}{V^2}$	$k^2{}_{0r}=\frac{\sigma^2}{V^2}$
415	6 from the last	$1-Aw^2\geqslant 0$	$1-Aw^2\leqslant 1$
415	3 from the last	Moreover $A\geqslant 1$	Above this $A\leqslant 1$
426	The last	(ii) $n=0.8$ from Table 5 and assume $n'=1.0$	(ii) $n=0.8$ $n'=1.0$ from Table 5
429	16	by himself applying by Goldie's method	by Goldie

Part II (Vol. XVIII, No. 2, 1935)

Page	Line	Read	For
86	7	—●°10h55 . . . . , Minor squall,	—●′ 10h55, Minor squall,
87	last	$\lambda=VT=11^{(m)}\times 6.4\times 60\div$ 4(km)	$\lambda=VT=11^{(m)}\times 7.5\times 60\div$ 5(km)
88	Fig. 7	indicates 5 m. p. s.	indicates 10 m. p. s.
92	14	statistical	sta istical
96	18	**4** On the . . . . . ,	**3** On the . . . . . ,
96	18	atmospheric	atomospheric
98	Equation (9)	$\left(\frac{1}{A-Bk_2}-\frac{1}{A-Bk_1}\right)\chi\equiv ax$	$\left(\frac{1}{A-Bk_2}-\frac{1}{A-Bk_1}\right)\equiv ax$
99	7 from the last	$A=a\bar{V}'10^3$	$A=a\bar{V}10^3$
99	6 from the last	$k=10^{-5}K$	$k=10^5K$
101	2 from the last	$k'<k_1$ or $k'>k_2$	$k'>k_1$ or $k'<k_2$
102	11	**5**. Some Discussions	**4**. Some Discussions
110	Fig. 32	25th. Feb. 1927	25th. Feb. 17.92
127	Table 7.	Upset of 53. b.	Upset of 53. d

Part III (Vol. XVIII, No. 4, 1935)

Page	Line	Read	For
174	Fig. 56 Scales of thermograph	16. 14. 12. 10.	18. 17. 16. 15.
177	Fig. 63	Meteorologram at Kyoto Meteorologram at Osaka	Meteorogram at Kyoto Meteorogram at Osaka
178	Table 8.	Press. Change ΔP Ôsaka 23h10m	Prss. Change ΔP Ôsaka 13h10m
186	5	4.2%	4.0%
188	4 from the last	**3**	3
197	7 (in Table 14)	* „ 20	„ 20 . . . . .

Part IV (Vol. XVIII, No. 6, 1935)

Page	Line	Read	For
319	Table 1 (in 1928)	14h4—22h5(14)*	14h4—22h5(14)
322	11	$\xi=0$ at $x=\pm l$ . . . . (4)	$\xi=0$ at $x=\pm l$
322	Equation (5) in { }	$\{\sin k(l+Vt)\sin km(x-l)$ $+\sin k(l-Vt)\sin km(x+l)\}]$	$\{\sin k(l+Vt)\sin km(x-l)$ $+\sin(l-Vt)\sin km(x+l)\}]$
322	last	in (6) and (8)	in (6) and (7)

On the Mechanism by which an Exploded Vertical Steam-Boiler Obtains the High Initial Velocity for its Projection

By Sojirô Haga

(Received Sept. 18, 1936)

Abstract

It is well-known that when a vertical boiler explodes, it is projected a considerable distance, causing no small danger. But the determination of the mechanism which manifests itself in this process is a problem yet to be solved. This paper outlines a hypothesis which seeks to explain the occurrence of this phenomenon under ordinary working pressure, and the explanation of two actual examples that appear to verify the newly proposed theory.

I. Introduction

The explosion of a steam-boiler often produces terrible and disastrous effects, taking lives and destroying property. At the time of the explosion, the entire boiler is hurled a considerable distance. The range of the projectile is sometimes 200–300 meters. For instance, at 7h 25m. a. m., June 29, 1910 before the beginning of the day's work, at Oaki Shipyard a vertical boiler in the machine shop of the yard exploded. A detailed technical investigation of this explosion has been reported by Dr. M. Tsutsumi.[1] This report is exceedingly valuable. The exploded boiler was 4 feet 11 inches in diameter, and 9 feet 4 inches in height, its permissible working pressure being 60 pounds per sq. inch. In this example, the corroding of the flanged part at the bottom of the fire-box brought on the initial rupture. The fire-box was wrenched from the boiler and only the boiler-shell was projected. The shell flew through the sheet-iron roof of the yard, and fell into the sea, 220 meters away from its seat. The fire-box was left behind, collapsed, and the rest of the accessories of the boiler were scattered in various directions. The photographs of Fig. 1 give some informations of this explosion.

The explosion of a vertical boiler at Kobe, April 19, 1932 is an another example. At about 5, 30 p. m., a small vertical boiler in a

1. The Journal of Society of Mechanical Engineers, Vol. XIII. No. 23. Oct. 1910 (in Japanese).

Fig. 1

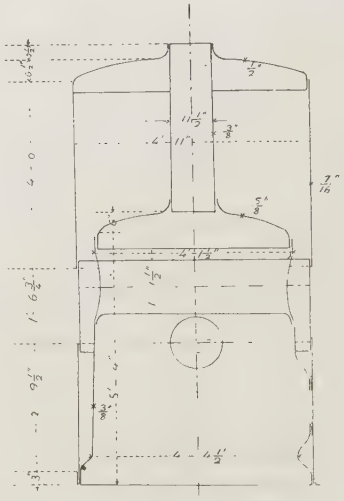
Photographs* of the vertical boiler explosion at Oaki Shipyard, Shinagawa, Tokyo.

A. The boiler-shell in the distant sea, viewed from the shore.

B. The boiler-shell projected to the distance of 220m. in the sea.

C. The collapsed fire-box resting near the original setting.

dye works exploded with a terrific sound, the entire boiler being projected to a distance of about 275 meters. The explosion took place during a recess before the beginning of the night work. The author has stated else-where[1] that it is frequently during recesses that explosions of this kind occur. He made a minute investigation of this Kôbe explosion. In Fig. 2 is given a sketch of the exploded boiler. The



D. The sectional elevation of the exploded boiler.

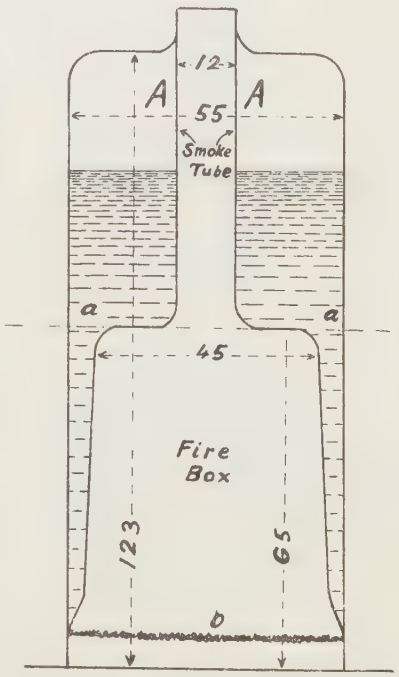
*The figures are reprinted from the report of Dr. M. Tsutsumi, loc. cit. 1. p. 245.

1. Treatise on the Fundamental Cause of Disastrous Explosion of Steam-Boiler, (1928) (The First Engine & Boiler Insurance Co. Ltd.).

thickness of the plate around the turn of the bend in the bottom of the fire-box having corroded to a feather-edge on account of wet ash, and being unable to withstand the pressure, finally ruptured. The fire-box did not come off, but was hurled along with the boiler.

It is reasonable and natural to suppose that the boiler, at the time of explosion, was under an excessive pressure. But the facts are quite contrary to this supposition. Those who actually work at the boiler, and who survive the explosion, invariably insist that the boiler-pressure has been kept within permissible limits. Some boiler-inspectors also hold this view. This naturally gives rise to the questions: By what mechanism does the vertical boiler obtain the high initial velocity necessary for its projection? Is this phenomenon possible under ordinary working pressure? The physical explanation of this question is difficult. Probably because of this difficulty no explanation of the phenomenon has yet been possible. In foreign countries, a doubt has been expressed as to whether it is due to some cause beyond the present range of scientific investigation. The author, after studying this problem for the last forty years, has formulated a new theory, which he publishes below, and concerning which he invites criticism and comment.

Fig. 2



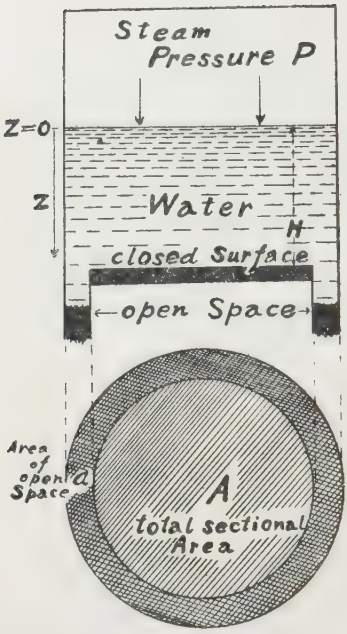
Sketch of the Vertical Steam-Boiler.
(Scale in cm.)

II. Theory

To make matters simpler, a cylindrical vertical boiler, as shown in Fig. 3, is considered.

When an aperture along the circumference of the boiler-bottom suddenly opens from any cause, the water in the boiler necessarily rushes out. For the construction of the equation of the motion of

Fig. 3



the boiler-water in this case, four allowable assumptions are made:

(i) It is assumed that the opening is of a considerable size, and that, with its outbreak, the boiler-water is set free from the pressure under which it is compressed. The boiler-water is regarded as a water-mass and treated like a solid, thus the complexity of hydrodynamical treatment is avoided. As, in this case, the pressure at the opening can be considered to be identical with the external pressure, the difference of pressure between the top and bottom surface of the water-mass is P, which is the motive force acting on the boiler-water.

(ii) Supposing that a super-heated water-layer exists near the surface of the boiler-water, the space produced by the out-rush of the boiler-water is filled up immediately by the steam into which some of the remaining water passes. Accordingly, it is reasonable to assume that the pressure P remains constant during the process.

(iii) As the boiler-water is unstable against the external pressure, a part of the heated water pushed out of the boiler speedily passes into steam and splashes explosively the other part of the water which came out simultaneously. From these considerations, it is to be assumed that the portion of the water-mass which pushes out of the boiler is immediately separated from the water remaining inside.

(iv) An estimation of the resistance-pressure is herewith attempted. The resistance-pressure on the closed portion of the bottom of the boiler is assumed to be $\frac{\gamma}{2}\rho(1-k)Av^2$, in which γ is a constant depending on the surface shape supposedly a number approximate to 1, ρ stands for the density of the water, $(1-k)A$ for the cross-sectional area of the closed surface, and v for the velocity of the water-mass. The resistance at the open end, in an ideal case, is zero, but, actually, it must be supposed to have some value, which may be estimated at $\frac{\sigma}{2}\rho a\left(\frac{v}{k}\right)^2$; σ, a constant depending on the conditions

of the open end and its neighbourhood, and having value near zero. Moreover, as the frictional moving resistance may be assumed to be fv^2 (f: a constant), the resistance specified in the above three terms is summed up in the formula $\alpha\rho Av^2$, where α is a constant with a value greater than zero. Now the co-ordinate (z) representing the relative position, of the upper surface of the boiler-water to the boiler itself, may be regarded as representing the motion of the whole water-mass.

Hence, the equation of the motion of the boiler-water is

$$\frac{dB}{dt}=PA+Mg-R \quad \cdots\cdots(1)$$

$$B\equiv(M_0-A\rho z)v=A\rho(H-z)v.$$

As, generally, $PA/Mg<1/10$, is a term which is due to gravity it can be disregarded. Since $R=\alpha\rho Av^2$, we get, from equation (1)

$$(H-z)v\frac{dv}{dz}=\beta v^2+\frac{P}{\rho} \quad \cdots\cdots(2)$$

where $\beta=1-\alpha$ $(\beta<1)$.

Integrating equation (2) by putting the boundary condition of $v=0$ at $z=0$,

$$\left.\begin{aligned} v&=\sqrt{\frac{2P}{\rho}}\sqrt{\log\frac{H}{H-z}} && \text{when } \beta=0\\ v&=Q\sqrt{\left(\frac{H}{H-z}\right)^{2\beta}-1} && \text{when } 0<\beta<1\\ v&=Q'\sqrt{1-\left(\frac{H-z}{H}\right)^{-2\beta}} && \text{when } \beta<0 \end{aligned}\right\} \quad (3)$$

where $Q\equiv\sqrt{\frac{P}{\beta\rho}}$ and $Q'\equiv\sqrt{\frac{P}{-\beta\rho}}$.

The speed at which the water rushes from the opening of the boiler is v/k, and the amount of water-mass ejected from the boiler in dt is $A\rho v dt$. Hence, the total amount of momentum carried out of the boiler during the process is

$$\int_0^T\frac{A\rho}{k}v^2dt=\frac{A\rho}{k}\int_0^H vdz.$$

Now, representing the mass of the boiler by M_B and its initial velocity by V_B, we get, according to the law of conservation of momentum,

$$V_B=\frac{M_0}{M_B}\frac{1}{kH}\int_0^H vdz \quad \cdots\cdots(4)$$

This equation gives the initial velocity of the projecting boiler. By integrating the equation (4) and substituting v for its value in equation (3), we get,

$$V_B = \frac{\sqrt{\pi}}{2k} \frac{M_0}{M_B} \sqrt{\frac{2P}{\rho}} f(\beta) \quad \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where $f(\beta)$ is the function of β, as shown in the following equations:

$f(\beta) \equiv 1$ when $\beta = 0$,

Table I

β	$f(\beta)$	β	$f(\beta)$
0.1	1.1	0.1	0.93
0.2	1.2	0.2	0.88
0.3	1.3	0.3	0.84
0.4	1.5	0.4	0.79
0.5	1.8	0.5	0.75
0.6	2.2	0.6	0.71
0.7	2.8	0.7	0.69
0.8	4.2	0.8	0.67
0.9	8.2	0.9	0.65

$$f(\beta) \equiv \frac{1}{(1-\beta)\sqrt{2\beta}} \frac{\Gamma\left(\frac{1}{2} + \frac{1}{2\beta}\right)}{\Gamma\left(1 + \frac{1}{2\beta}\right)}$$

when $1 > \beta > 0$,

$$f(\beta) \equiv \frac{\sqrt{-2\beta}}{1-\beta} \frac{\Gamma\left(1 + \frac{1}{-2\beta}\right)}{\Gamma\left(\frac{1}{2} + \frac{1}{-2\beta}\right)}$$

when $\beta < 0$.

Γ is gamma function. Table I shows the numerical value of $f(\beta)$. The exact value of β is difficult to determine, but it is supposed to lie within the range of ± 0.3. Further, because $f(\beta)$ lies between 1.3 and 0.84, we adopt $\beta = 0$, namely, $f(\beta) = 1$, as our norm.

III. Verification by the two actual examples

The theory above proposed is applied to the two actual examples described in Section I. for verifications.

Ex. I. The explosion of a vertical boiler at Kobe, Apr. 19, 1932.

The constants regarding this boiler necessary for the application of the theory are:—

$A = 2.3 \times 10^3$ (cm^2) $\quad a = 0.7 \times 10^3$ (cm^2)

$M_B = 1.5 \times 10^5$ (g) $\quad M_0 = 1.1 \times 10^5$ (g)

$k = a/A \fallingdotseq 0.31$ $\quad \rho \fallingdotseq 0.9$ (150°C).

The numerical value of the pressure carried is unknown, but it is possible to get an approximate value from the inspector of the boiler, who estimates it to be 3 or 4 atmospheres. On the other hand, the range of projectile is found, on measurement, to be exactly 275 meters. Judging from the damage caused to surrounding objects, the emergent angle was about 60°. Investigation concerning the falling of the boiler shows that it returned to the ground at about the same angles at which it ascended, i. e., 60°–70°. This is inferred from the fact that the boiler made its descent through an irregular network of telephone and electric lines without snapping or bruising any one of the wires. From these observed facts, the numerical value of V_B is calculated

by means of the well-known formula, $V_B=\sqrt{Dg/\sin 2\theta}$, in which friction is neglected. We get, in this instance, $V_B=53.2$ m. p. s. The value must actually be estimated as a little larger than this result, so it is assumed to be $V_B=6\times10^3$ (cm/sec.).

Now, in the standard case, in which $\beta=0$, the value of the pressure P calculated according to the author's theory, is found to be $P=3.5\times10^6$ (C. G. S.), namely, 3.4 atm. (the absolute pressure being 4.4 atm.). This is the pressure of saturated vapour at 150°C. Here, however, there is no ground for assuming $\beta=0$, which is adopted only as a provisional value. If it is assumed to be $\beta=0.3$, then the absolute pressure must be 3 atm. Because this value agrees approximately with that of the pressure P estimated by the inspector of the boiler, it is supposed to have been in the vicinity of $\beta=0$. In this instance, the time required for the exit of the whole boiler-water is calculated, (being regarded as the standard case),

$$T=\int_0^H \frac{dz}{\sqrt{\frac{2P}{\rho}\log\frac{H}{H-z}}}=\frac{M_0}{A}\sqrt{\frac{\pi}{2\rho P}}\fallingdotseq 0.035 \text{ (sec.)}.$$

In other words, the whole process came to completion in about 1/30 sec. Thus it is seen that the author's theory offers an adequate physical explanation for this actual case. But the question remains, why did the boiler take the emergent angle, 60°? It is no small task to answer this question. But the mode of the initial rupture at the bottom was asymmetric, and some rotative power generating on this account may have produced this result.

Ex. 2. The explosion in the Oaki Shipyard, June 29, 1910.

The necessary data for the application of the author's theory are enumerated below :—

(i) The report decisively states that the pressure at the time of explosion was about 25 pounds per square inch (1.5 atm.).

(ii) Although the emergent angle is unknown, the range of the projectile was about 220 meters.

(iii) The mass of the projectile was 1.2×10^6 (g).

(iv) The water contained in the boiler is supposed to have been 1.0×10^6 (g) in quantity.

(v) $k=a/A\fallingdotseq 0.4/1.7$.

Regarding this explosion as belonging to the standard case, i. e., supposing $\beta=0$, the unknown V_B is calculated by the formula (3),

$$V_B=4\times\frac{1.0\times10^6}{1.2\times10^6}\sqrt{\frac{2\times1.5\times10^6}{0.9}}\sqrt{\frac{\pi}{2}}$$
$$\fallingdotseq 54\times10^2 \text{ (cm/sec.)}.$$

V_B is found, namely, to be 54 m. p. s. If we assume the unknown emergent angle to be 60°, as it was in the former example, we get,

$$V_B = \sqrt{\frac{220 \times 9.8}{0.87}} \fallingdotseq 50 \times 10^2 \text{ (cm/sec.)},$$

i. e., about 50 m. p. s., which approximately coincides with the value obtained in the former example.

Because actual examples are accidental failures, and not experimental observations, a full and complete verification of the theory is impossible. But enough has been stated above to show that the theory is reasonable.

IV. Discussion

There remains a question, however, as to whether the internal pressure is an ordinary or an impulsive pressure. Experiments on this point have been frequently undertaken, but they are very difficult. On the other hand, the author wishes, from a theoretical standpoint, to set up a more complete hydrodynamical and thermodynamical theory concerning this question ; but this may be too difficult a task for him at present. About 50 years ago, two famous scientists, Airy and Rankine, considering that the energy enclosed in the boiler, being suddenly set free, gives rise to an explosion, used their method to calculate the available thermodynamic energy. This quantitative treatment of the boiler explosion, though it was adopted by succeeding engineers, does not explain by what mechanism the boiler is hurled out, or in other words, the origin of the boiler's kinetic energy. The author's theory clears this point. Throughout the whole process of explosion, the thermal energy plays the most important part, as these scientists hold. But, for the boiler to be hurled out, this thermal explosion acts in an indirect way. The author believes that his theory is in harmony with existing theories, and that engineers who have much experience concerning boiler-explosions admit such a mechanism as this theory implies. Moreover, given a formula by which the initial velocity of the boiler is obtained, physicists and engineers will be able to judge the merits of the author's theory. In this paper technical and industrial considerations have been mostly omitted, but they will in near future be published as a sequal to the author's " Treatise on the Fundamental Cause of Disastrous Explosion of Steam-Boiler."

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